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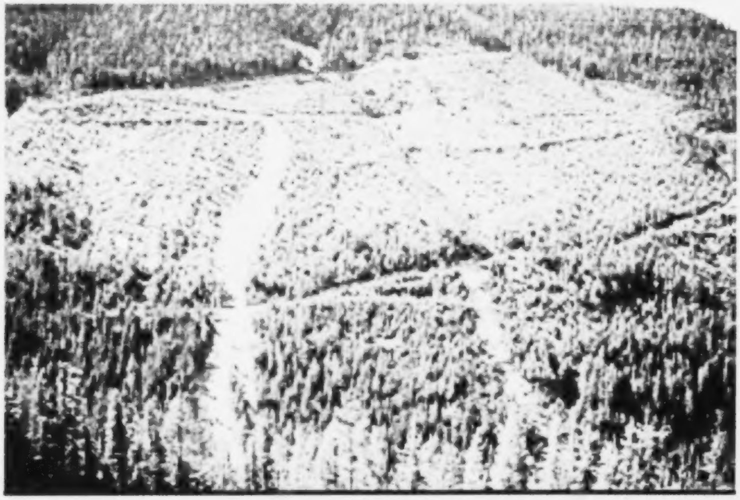

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Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proceedings May 23–25, 2001

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Peter Jordan and Julie Orban (editors)

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PREFACE

The "Terrain Stability and Forest Management in the Interior of British Columbia" workshop, held in Nelson on May 23–25, 2001, was the first conference on landslides, terrain stability, and related forest management issues to be held in the British Columbia Interior. The purpose of the workshop was to bring together research scientists, engineers, and foresters who have been dealing with this subject since the introduction of the Forest Practices Code in 1995. An important objective was to present the results of several research projects on landslides and terrain stability, which were nearing completion under the 5-year period of Forest Renewal British Columbia research funding that began in 1996.

The Forestry Continuing Studies Network and the B.C. Ministry of Forests, Nelson Forest Region organized the workshop. The Association of Professional Engineers and Geoscientists of British Columbia, Division of Engineers and Geoscientists in the Forest Sector (DEGIFS), and the Arrow Innovative Forest Practices Agreement (IFPA) sponsored the event. Twenty-three oral presentations and 14 posters were presented at the workshop, covering a range of landslide research, geotechnical engineering, and applied forestry topics.

On two field trips, participants visited sites of interest in the West Kootenays. Approximately 200 people attended the workshop.

These proceedings include 16 of the papers presented at the workshop. These papers have been peer-reviewed and revised over the 12 months since the workshop. The digital version of the proceedings, to be distributed on compact disc and on the Internet, also features appendices containing other products of the workshop, including abstracts, notes and graphics attached to the abstracts, slide presentations, and field trip guides. Appendix 2 has not been reviewed or edited.

Note regarding British Columbia government ministries and the Forest Practices Code: As these proceedings go to press, the British Columbia government has announced major changes to the Forest Practices Code and to government ministries, forest regions, and districts. Some papers in these proceedings refer to government ministries and their geographic entities, and to regulations or guidebooks of the Forest Practices Code. All such references are current as of the date of the workshop, May 2001.

ACKNOWLEDGEMENTS

First of all, we would like to thank the many foresters, geoscientists, engineers, and other interested people who attended the "Terrain Stability and Forest Management in the Interior of British Columbia" workshop. Their participation made the workshop a success.

The workshop would not have been possible without the hard work of Kandy Akselson of the Forestry Continuing Studies Network, who organized the facilities, food, registration, and other practical details.

Kevin Turner and Joe Alcock served as the organizing committee, in the months leading up to the workshop. Brent Ward, Tim Smith, Kim Green, Terry Rollerson, and Kevin Turner were session chairs, and Joe Alcock organized the poster session. Nichole Boultbee helped with the field trips and posters, prepared the field trip guides, and along with Emilee Fanjoy, looked after the audio-visual equipment. Dwain Boyer, Doug Nicol, and Peter Jordan led field trips, and Carol Wallace and Marc Deschenes helped on the field trips.

This workshop and proceedings were supported by a research grant to the senior editor by Forest Renewal BC, project no. KB97202.

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Donna Creek Washout-Flow—What Did We Learn?

JAMES W. SCHWAB

ABSTRACT

The 1992 Donna Creek washout-flow has the form of a large dendritic-shaped gully, 5 m deep at the headscarp with steep side walls extending up to 30 m deep. The gully covers a land area of approximately 4.5 ha, from which 422 500 m^3 was eroded. The Donna Creek washout-flow was caused by changes made to the natural hillslope runoff. The changes were a direct result of water capture and routing along ditches of branch roads constructed for forest harvesting. These roads did not have sufficient cross-drains or culverts to permit water to cross the roads and return to natural drainage channels. The road capture and rerouting of runoff increased the drainage area to the site of the washout by 9.8 times. The hillslopes above Donna Creek experienced high rates of runoff on the days preceding the event (May 25–June 2, 1992). At peak flow, the volume of water delivered to the site was estimated at 0.23 m^3/s, giving a daily total of about 20 000 m^3 of water. The total volume of water delivered to the washout between May 23–June 2 was estimated at about 143 000 m^3, a 7.3-fold or 730% increase over expected normal runoff. This excessive volume of water flowing over and into an area of a highly erodible glaciofluvial/glaciolacustrine terrace probably destabilized a steep spoon-shaped gully that opened a face for seepage and collapse of loose silts, sands, and gravels. Catastrophic seepage face erosion resulted in an avulsion of material. Debris flow surges rapidly transported material down an adjacent gully into Donna Creek. Large quantities of sediment entering Donna Creek, combined with high spring runoff, triggered a debris flood that transported debris 6 km down Donna Creek to Manson River.

INTRODUCTION

A large catastrophic washout-flow occurred on June 2, 1992, at Donna Creek, a major tributary of Manson River, about 75 km northwest of Mackenzie, B.C. (Figure 1). The landslide occurred in what appeared as a dry gravelly terrace, situated below a forested slope on which logging road subgrade had been constructed. In terms of cause, magnitude, and landslide process, the event is of particular interest to earth scientists. Moreover, the event also had significant implications for forest management in British Columbia:

- The washout-flow occurred just days prior to a scheduled release of 50 000 kokanee into Donna Creek. In June of the previous 3 years, 200 000

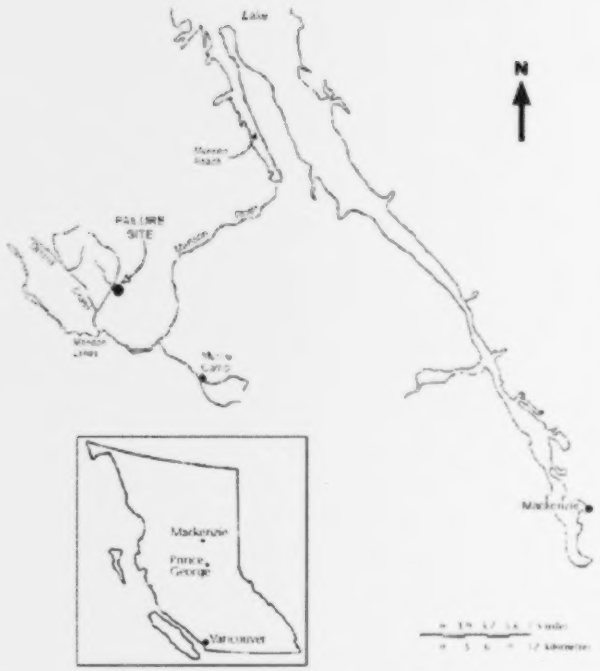


FIGURE 1 *Donna Creek, located northwest of Mackenzie, B.C.*

fingerling kokanee had been released into Donna Creek at the Manson Mainline road bridge. Kokanee were expected to return from Williston Lake to spawn in the fall of 1992 with the first major return in the fall of 1993. No records are available on actual kokanee returns for Manson River.

- The Forest Practices Code of British Columbia was enacted in 1995. In an attempt to prevent erosion and landslides, forest road regulations now require that drainage systems be built concurrently with subgrade construction, and that drainage systems be fully functional to accommodate surface and subsurface runoff.
- The forest licensee was charged under the *Fisheries Act* Section 35 (1) *No person shall carry on any work or undertaking that results in the harmful alteration, disruption or destruction of fish habitat*; and Section 36 (3) *No person shall deposit or permit the deposit of a deleterious substance of any type in water frequented by fish.* The offences were treated as indictable. A lengthy preliminary hearing took place through 1996–1997. Based on legal arguments, the charges did not proceed to trial in the Supreme Court of British Columbia.

This paper explores the causal factors and the landslide/erosion processes of the 1992 Donna Creek washout-flow.

GENERAL CLIMATE AND HYDROLOGY

Climate for the regional area is characterized by long, cold winters and cool, short summers. Total precipitation at lower elevations ranges from 400 to

700 mm. Winter precipitation is dominated by snow. Snow accumulations range from 400 to 1500 mm snow-water equivalent for Alken Lake at 1040 m above sea level (a.s.l.) and Pine Pass at 1430 m a.s.l., respectively. Streamflow for the region is dominated by spring snowmelt. Streams begin to rise with the onset of snowmelt in late March–early April, and rise rapidly with the contribution of mid- and higher elevation melt commencing in early May. Annual peak streamflow (peak runoff) occurs in late May–early June. Lower slopes in the immediate vicinity of the washout normally contribute to the early spring runoff. The land area that contributes water to the washout site is located at mid-elevations (1100–1450 m a.s.l.). Therefore, the main runoff from the hillslopes above the washout occurs during peak spring runoff generated for Donna Creek watershed.

GENERAL GEOLOGY AND TERRAIN

Surficial geology maps indicate an extensive glaciofluvial terrace along the lower slopes of Donna Creek valley (B.C. Ministry of Environment 1977; Plouffe 2000). The upper limit of the glaciofluvial terrace near the failure is at 1150 m. A glaciolacustrine terrace modified by erosion is shown between 900 and 1000 m elevation in the lower reaches of Donna Creek watershed. The maps indicate that the glaciolacustrine sediments extend upstream to the 1992 Donna Creek failure. The washout-flow is situated on a terrace located at mid-elevation on the east side of Donna Creek valley. Elevation of Donna Creek floodplain is 975 m and the hilltop above the washout is 1450 m. The landform rises steeply above the floodplain at 37° to 1050 m. The terrace surface slopes uphill in a series of short steep rises with an overall slope gradient of 10°. Visible within the erosion crater is a complex sequence of glaciofluvial sands and gravels overlying glaciolacustrine sands and silts. These sediments were deposited close to glacial ice. A thin discontinuous layer of compact glacial till covers mica schist bedrock (Ferri et al. 1988), which is exposed within the scarp. Moderately fine-textured morainal and colluvial materials mantle the surrounding slopes above the terrace. Figure 2 provides a schematic diagram of the relative positioning of these surficial materials.

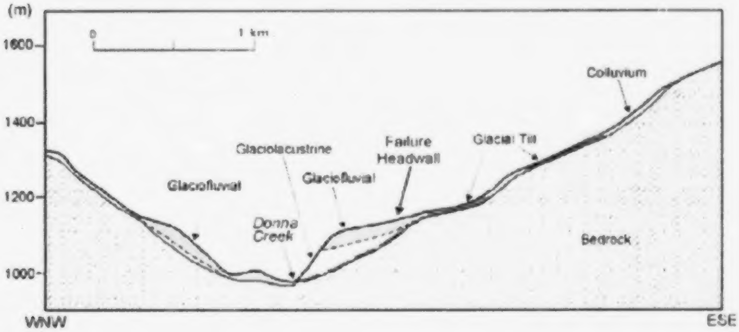


FIGURE 2 *Schematic representation of the relative positioning of surficial materials. (Vertical exaggeration 2.5 x, stratigraphic boundaries are conceptual only.)*

The crater eroded by the washout is a large dendritic gully, 5 m deep at the head scarp with steep side walls extending up to 30 m deep (Figure 3). The crater extends back 290 m from a deeply incised adjacent natural gully and covers a land area of approximately 4.5 ha, from which 422 500 m^3 was eroded. Eroded material was rapidly transported by debris flow surges down the established gully across Donna Creek floodplain, a distance of 400 m. Destabilization of the gully side walls (40°) resulted in the addition of a few thousand cubic metres of material to the flows. Approximately 62 500 m^3 of debris and sediment were deposited on the fan where the main gully empties onto the floodplain—few trees were left standing (Figure 4). A resultant

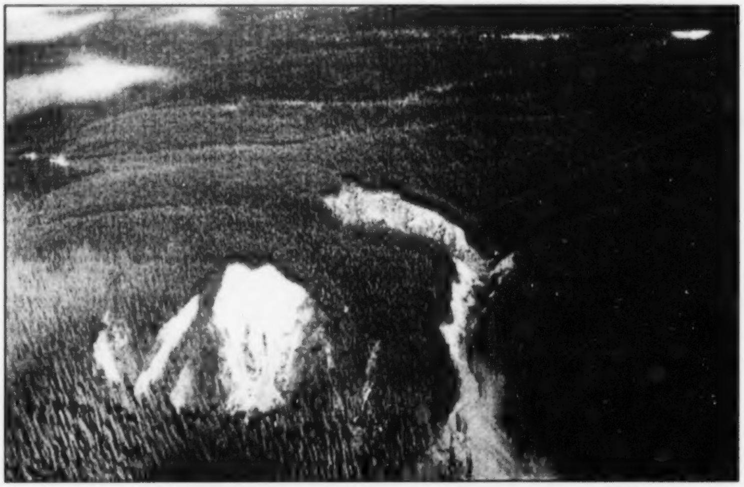


FIGURE 3 *Crater eroded by the washout-flow. Note landform and roads on slope above.*

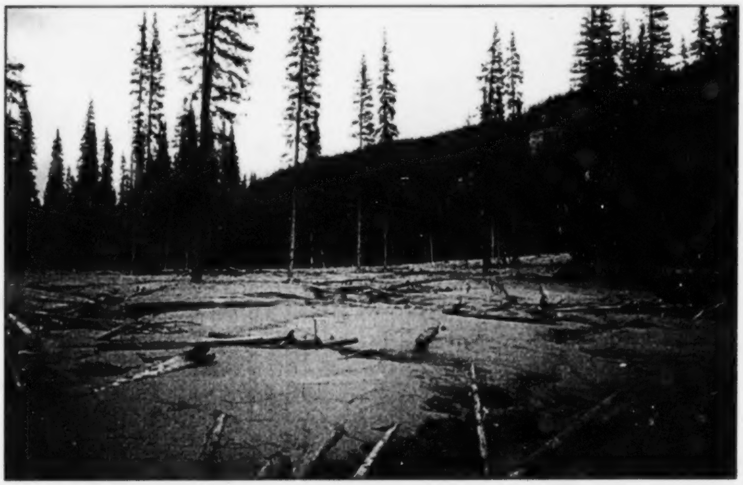


FIGURE 4 *Debris fan. Note few standing trees and 10 m high debris flow splash on trees.*

debris flood down Donna Creek transported and deposited 360 000 m^3 of sediment and debris on the floodplain and behind logjams over 6 km toward Manson River (Figure 5).

Figure 5, a composite map of the washout-flow and hillslope, depicts topography, drainage basins, road locations, water flow directions, and site locations (1, 2, 3, 4, 5, and 6) referred to in the text.

FOREST DEVELOPMENT

The hillslope above the washout was forested, with the exception of road rights-of-way and roads constructed for timber harvesting. Construction of DC1000 branch road directly above the terrace started in 1988. Additional branch roads were constructed in January and February 1990 to access a proposed cutblock. Branch road DC1300 switchbacks up the slope to access the top of the proposed block. Further block access was obtained with mid-slope roads at lower and higher elevations, DC1310 and DC1320, respectively.

DRAINAGE BASINS

The established surface drainage on the hillslope above the Donna Creek washout occurs via four basins. The basins are poorly defined topographically on the steep uniform upper hillslopes, in contrast to deeply incised gullies cut through the glaciofluvial/glaciolacustrine landform, with

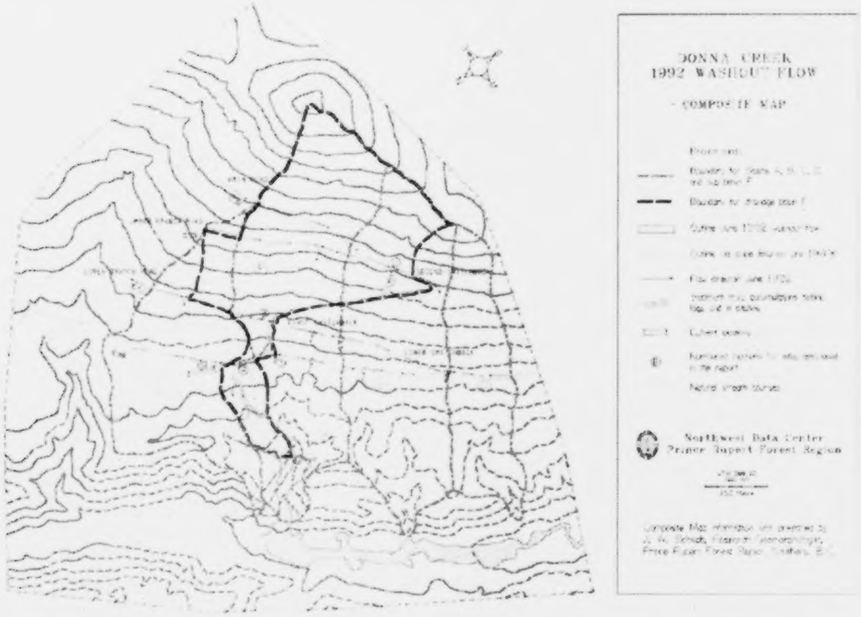


FIGURE 5 *Composite map—depicts topography, drainage basins (A–F), branch roads, water flow directions, and site locations (1–6) referred to in the text.*

outlets onto the Donna Creek valley flat. The basins designated as A, B, C, and D drain land areas of 39.3, 61.2, 49.5, and 24.4 ha, respectively. Basin E, a sub-basin of basin B, drains a land area of 5.8 ha. Basin E is important in that its catchment encompasses the 1992 washout and drains into the incised gully channel of basin B.

DRAINAGE ALTERATION

The construction of the DC1000 road dissected the natural drainage basins on the hillslope. A natural berm that formed the upper boundary for basin E was breached by a crawler tractor bladed "push-out" during or sometime after construction, to permit water to flow away from a low point on the road.

The DC1300 road contained four culverts (cross-drains) over a distance of approximately 2170 m. Two of the culverts were situated at lower elevations, along the road before the switchback at the DC1310 junction. Above the switchback, constructed drainage consisted of two culverts over a distance of approximately 1540 m. The steep road grade, running from 11.2 to 16.8% between the first and second switchback, contained no cross-drains (culverts, cross-ditches, or water bars) for approximately 700 m. DC1310 contained one culvert placed close to the junction of the DC1300 road. DC1320 contained no culverts or constructed cross-drains.

The construction of DC1300, DC1310, and DC1320 in 1990 altered the natural surface and subsurface drainage on the slope by collecting water along ditches and directing flow out of the natural drainage basins to new outlet locations 1, 2, 3, 4, and 5 above the washout site. Erosion along ditches and a sediment trail mark the path of water flow. This alteration of the hillslope drainage by the road network created a new drainage catchment area that covered approximately 56.9 ha (basin F). This expanded drainage into the washout represents a catchment increase of 9.8 times (56.9 ha/5.8 ha).

The major collection and channelization of water occurred along the DC1300 road above the second switchback, and further downhill along the steep section above the first switchback. Water flow eroded a deep channel in the ditch above the first switchback (Figure 6). This sediment filled the ditch and culvert at a low spot on the DC1310 road (location 2). Sediment-laden water flowed over the road, spilled out of the natural drainage channel below the road, and flowed overland down to the DC1000 road. Water and sediment exceeded the capacity of the drainage constructed along the DC1000 road (locations 3–5). Most water crossed the road via the bladed "push-out" onto the terrain directly above the washout (location 4, Figure 7). A sediment trail provides evidence of overland flow down to the terrace and crater head wall (Figure 8).

SNOWMELT RUNOFF

Air temperature and precipitation recorded for the area show consistently cool conditions (0–5°C) prior to May 15 with a significant drop in temperature on May 15 coupled with a large snowfall. A very rapid rise in temperature occurred on May 22, reaching an mean daily temperature of 17°C. An above-average snowpack, coupled with additional late May snow, followed by an increase in temperature, resulted in a rapid snowmelt in the elevation band of 1100–1500 m. Simulated snowmelt rates for the slopes above the failure indicate peak values of close to 4.5 cm per day (U.S. Army Corps of Engineers 1960). The entire area above the washout, combined by the altered road drainage into a single basin "F," was contributing a high rate of water delivery—possibly at rates higher than a 50-year rainstorm event recorded in the spring of 1990.

The hillslope above Donna Creek experienced high rates of runoff from snowmelt from May 25 to June 2, 1992. Flows were determined using the

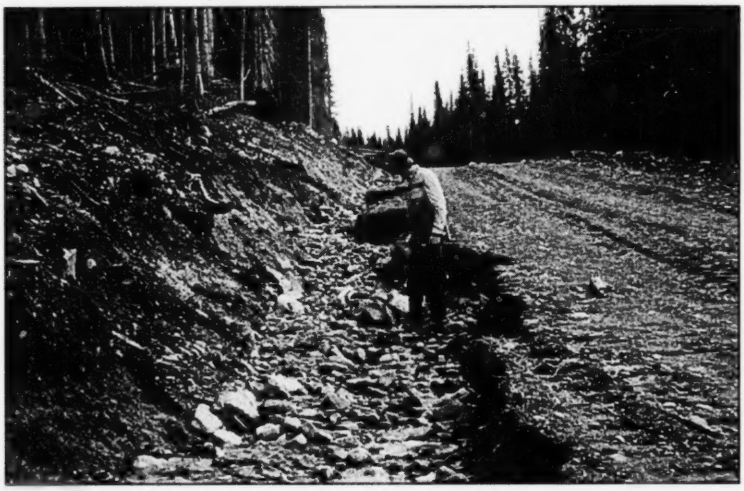


FIGURE 6 *Ditch erosion above first switchback, location 2. Peak water flow was estimated at 0.31 m^3/s.*

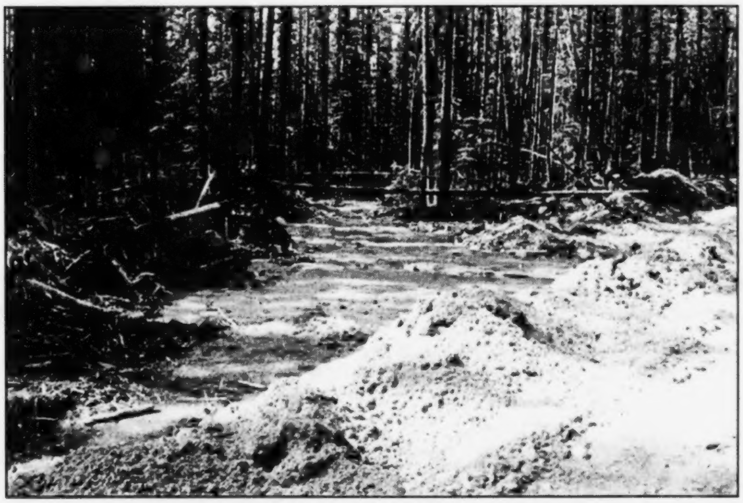


FIGURE 7 *Water delivered via the crawler tractor bladed "push-out" (location 4) is 0.23 m^3/s—a daily total of about 20 000 m^3/s.*

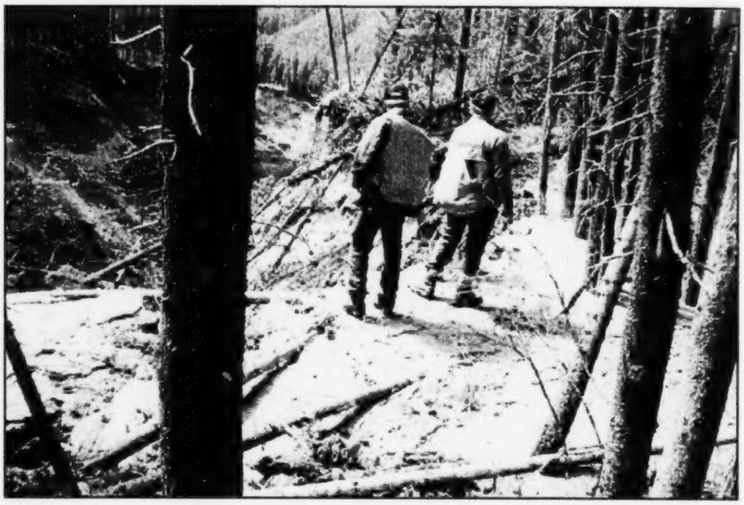


FIGURE 8 *Sediment trail shows evidence of overland flow into the crater head wall.*

Manning equation. Calculations for location 2 indicate a maximum flow of 0.31 m^3/s. This value compares well to the simulated average daily value of 0.28 m^3/s estimated for May 31, the date of the highest runoff at the site (total daily snowmelt and rainfall).

At peak flow, the volume of water delivered to the washout site via the push-out at location 4 was determined to be 0.23 m^3/s—a daily total of about 20 000 m^3 of water. This is equivalent to approximately 25 times the volume found in an average-size community swimming pool (800 m^3; length 25 m, width 15 m, average depth 2.1 m). The total volume of water delivered to the area above basin E from May 23 to June 2 was about 193 000 m^3. An estimated 74% flowed to the washout via the bladed "push-out" (location 4). This equals about 143 000 m^3 or approximately 180 average-size community swimming pools over the 11 days. The estimated volume delivered to basin E was 7.3 times or 730% that received under natural conditions.

EROSION PROCESS

The event had a character typical of catastrophic seepage face erosion or washout that has been observed in glaciofluvial sands, silts, and gravels. For example, the grand campus washout of 1935 at UBC Vancouver (Williams 1966); Maryhill gravel pit washout, Coquitlam River valley (Allen 1957); gully-flow in deltaic sands and silts, Moise River, Quebec (Dredge and Thom 1976); caving erosion (Hungr and Smith 1985); gully erosion / caving erosion found in the Coquitlam River valley (Siebert 1987); and seepage-face erosion (Parker and Higgins 1990). Catastrophic seepage face erosion was also observed at Bowser River in 1995, a result of the diversion of a small stream by beaver onto a glaciofluvial terrace of sands and silts—no surface water flow reached the catastrophically formed gully.

A schematic representation of catastrophic seepage face erosion is presented in Figure 9. Under normal conditions, seepage exits the slope without

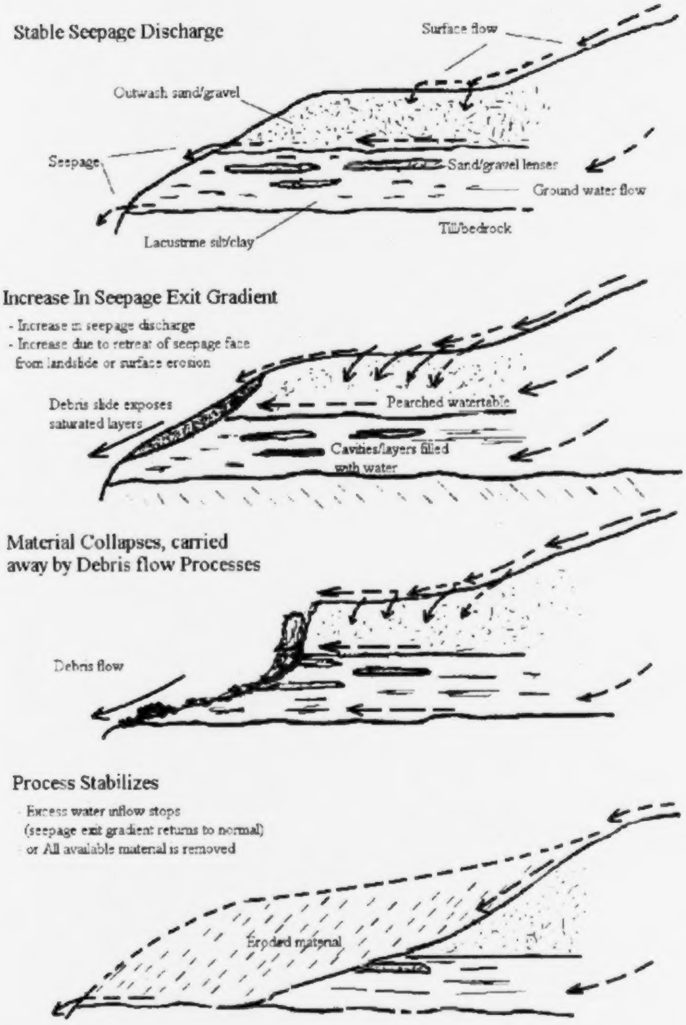

Stable Seepage Discharge
Surface flow
Outwash sand/gravel
Seepage
Sand/gravel lenses
Ground water flow
Till/bedrock
Lacustrine silt/clay
Increase In Seepage Exit Gradient
- Increase in seepage discharge
- Increase due to retreat of seepage face from landslide or surface erosion
Debris slide exposes saturated layers
Pearched watertable
Cavities/layers filled with water
Material Collapses, carried away by Debris flow Processes
Debris flow
Process Stabilizes
- Excess water inflow stops (seepage exit gradient returns to normal)
- or All available material is removed
Eroded material

FIGURE 9 *Schematic representation of catastrophic seepage face erosion. Concept adopted from Siebert (1987).*

causing erosion as the ground slope of the seepage face has adjusted to the highest recurrent seepage exit gradient and resulting seepage forces. A change in the discharge conditions results in an increase in seepage exit gradient above a critical value. (Seepage exit gradient is the slope of the piezometric surface adjacent to the drainage discharge point.) This increase in exit gradient may result from a rapid increase in groundwater discharge or sudden removal of material from the seepage face by a landslide or by running water. If the resultant erosion is of sufficient intensity, the retreating seepage face uncovers material with greater groundwater pressure, the exit gradient increases, and a continuing chain reaction results (Dr. O. Hungr, Univ. B.C., Earth and Ocean Science, Vancouver B.C., pers. comm., 1997).

The large volume of surface water entering the site and the high infiltration rates of the gravelly sands permitted water to percolate through to depth. (The hydraulic conductivity measured for the glaciofluvial sands and gravels was 9.7×10^{-3} and for the glaciolacustrine silts, 1×10^{-6}.) Thus, surface water added to the site greatly increased the amount of water delivered to water-bearing layers (aquifers) in the complexly bedded sands, silts, and gravels found within the terrace. Through-flow of the subsurface waters appears to have concentrated above fine-textured stratigraphic layers, and over impermeable layers of compact till and bedrock found in the site. Subsurface bedrock may also have helped to concentrate flows toward the failure outlet.

The substantial surface and subsurface flow directed toward location 6, a site of a small spoon-shaped depression on the terrace scarp, is assumed to have provided the trigger conditions. A rapid increase in seepage exit gradient resulted from a sudden increase in groundwater discharge or from the sudden removal of material from the seepage face by a landslide and/or running water. The removal of material on the scarp face uncovered material with greater groundwater pressure—generally confined, water-charged aquifers. The rapidly retreating seepage face then became the locus for caving failures and the convergence of surface and subsurface flow. At some point, the Donna Creek event reached a threshold where the erosional processes began to feed each other: headward advance, caving, collapse, and flow surges of liquefied material—hence, the sudden apparent avulsion of material that was first noticed on the morning of June 2, 1992. Debris flow surges rapidly transported a large volume of material from the site, down the adjacent gully channel, and down to Donna Creek. The excessive flow down the adjacent gully destabilized the steep gully side walls (slopes > 40°). Debris slides from these side walls entering the gully may have triggered debris flows or just added volume to the flow surges down the channel. Splash from flow surges is evident up to 5 m high along the gully side wall and 8 m high on the few trees left standing close to the apex of the fan. Large quantities of sediment and debris entering Donna Creek, combined with high spring runoff, triggered a debris flood (debris jam formation, breakage, and subsequent flow surges down the creek). Large volumes of sediment were deposited along the floodplain and temporarily stored behind logjams within the stream channel.

The description of the processes going on during this catastrophic event give rise to the question of what or how the event should be classified. The outcome is the formation of a large dendritic gully similar in shape and size to other gullies in the glaciofluvial/glaciolacutrine landform; hence, gully erosion or erosion by running water—a washout. Landslide processes are also involved: the collapse, dilation of material, and extremely rapid debris flow of liquefied material to Donna Creek; hence, flow or debris flow. The term "washout-flow" thus describes the overall complex landslide process.

Piping is a term commonly used to describe subterranean erosion (Parker and Higgins 1990). Terrain undergoing subsurface erosion often exhibits hollows or collapsed depressions aligned along routes of subsurface erosion. These features, combined with accompanying cave or pipe, are generally observed in arid climates in landforms composed of silt and clay. Piping is also used to describe soil pipes and/or water movement in forest soils in particular along root channels and along small erosion conduits in surficial materials. Thus, piping is often a confusing or ambiguous term as related to landslides. On the other hand, piping may have been present in the landform before the event and active during the landslide process. Although, in noncohesive materials this cannot be substantiated, in that features would not survive in sands, silts, and gravels as found at Donna Creek. More appropriately, catastrophic seepage face erosion describes the sudden change in the discharge conditions that result in an increase in seepage exit gradient, the subsequent convergence of surface and subsurface flow, retreating seepage face, caving, collapse, and debris flow surges.

GENERAL DISCUSSION

The catastrophic washout debris flow at Donna Creek serves well to emphasis a very basic concept in our knowledge of water source areas (drainage basins) and how roads modify water movement. A road constructed on a hillslope intersects many poorly defined micro-topographic drainage basins. If drainage is not adequately provided, the capture and redirection of surface and subsurface water in effect can expand the drainage area to an existing basin outlet. The subsequent increase in discharge into a different drainage basin (a result of an expanded drainage basin) can exceed the normal discharge of the channel or the ability of the site to disperse water, which may lead to slope failure. Water captured along forest roads is often directed off into the bush to disperse outside the natural drainage basin. The subsequent erosion is often not observed, in that erosion occurs out of sight from roads. Even though a site appears well drained, it may not handle an excessive increase in water. For example, well-drained sands and gravels of a glaciofluvial terrace overlying glaciolacustrine silts are highly erodible and subject to failure. Likewise, a kame terrace, composed of sands, silts, and gravel, situated on a hillside is highly erodible and subject to failure with the addition of excessive water.

Another important point emphasized by Donna Creek events ties closely to present requirements in the Forest Practices Code, Forest Road Regulations. Drainage basins are modified at the time of subgrade construction. As such, drainage systems must be installed and fully functional to accommodate surface and subsurface drainage runoff at the time of construction, and the drainage system must maintain surface drainage patterns as per B.C. Reg.106/98 Part 3.12 (1) (a) and Part 3.13 (1) (a) (Province of British Columbia 2000). If this practice had been implemented when roads were constructed in 1990 at Donna Creek, the washout-flow would not have occurred in June 1992. It is important to place adequate and functional drainage in a road subgrade at the time of construction.

The first reaction when we observe a large landslide or erosion event caused by an inappropriate practice on forest land is to find blame. However, it is important to step back and assess our involvement. We all travel forest roads for work and recreation access. How often do we see water captured and diverted long distances down a ditch, water flowing across a road in excess capacity for the drainage system, or the consequences of mass erosion? Often, these situations are observed but frequently the cause is not investigated or nothing is done to stop or correct the problem. In the Donna Creek situation, water capture and diversion by branch roads occurred during two springs prior to the spring of 1992. It is hard to believe that no one observed or took action to correct drainage issues. In many respects, all of us working in the forest industry must take responsibility. We must observe, report, and correct drainage problems with roads to prevent serious erosion, landslides, and subsequent environmental degradation.

SUMMARY

The Donna Creek washout-flow was caused by changes made to the natural hillslope runoff. The changes were a direct result of water capture and routing along road ditches. These roads did not have sufficient cross-drains or culverts to permit water to cross the roads and flow into natural drainage channels. Excessive volumes of water were delivered onto highly erodible sands, silts, and gravels of a glaciofluvial/glaciolacustrine terrace at 730% that received under natural conditions. A rapid increase in seepage exit gradient resulted from the sudden increase in groundwater discharge, combined with a possible sudden removal of material at the terrace scarp by a landslide and/or running water. Catastrophic seepage face erosion describes the sudden change in the discharge conditions that result in rapidly retreating seepage face, caving, collapse, and debris flow surges of the June 1992 washout-flow. This catastrophic event at Donna Creek emphasizes a very basic concept in our knowledge of water source areas (drainage basins) and how roads can potentially modify water movement and cause destructive landslides.

ACKNOWLEDGEMENTS

I gratefully acknowledge Marten Geertsema for his assistance during investigative fieldwork in June and July 1997, Dr. Brent Ward for his discussion and advice on describing the sediments, and Cheryl MacMillan for GIS support. An initial investigation of the cause and impacts of the Donna Creek slope failure was undertaken in 1992. Pierre Beaudry described the hydro-climatic conditions and Dan Hogan, the stream channel impacts and recovery. The 1992 investigative team consisted of Brian Clapp, Carl Erickson, Dave Francis, Bruce Jamieson, Dave King, Paul Sandorn, Jim Schwab, Dave Wilford, and Gary Zsomber.

LITERATURE CITED

Allen, J.F. 1957. Landslides, washouts and mudflows in the Lower Fraser Valley, B.C. B.A.Sc. thesis. Univ. B.C., Vancouver, B.C.

British Columbia Ministry of Environment. 1977. Manson Lakes 93w/9 landforms (1:50,000 map).

Dredge, L.A. and B.G. Thom. 1976. Development of a gully-flow near Sept-Iles, Quebec. Can. J. Earth Sci. 13:1145–51.

Ferri, F.D., M. Melville, G.A. Malensek, and N.R. Swift. 1988. Geology of the Manson Lakes map sheet (NTS 93N/9). Open File 1988-12a. B.C. Min. Energy, Mines and Petroleum Resour., Geol. Surv. Br., Victoria, B.C.

Hungr, O. and D. Smith. 1985. Landslides and development in the Lower Mainland, British Columbia. The B.C. Professional Engineer 36(4):11–4.

Parker, G.G., Sr. and C.G. Higgins. 1990. Piping and pseudokarst in drylands, with case studies. *In* Groundwater geomorphology: The role of subsurface water in earth-surface processes and landforms. C.G. Higgins and D.R. Coates (editors). Boulder, Colo., Geol. Soc. Am., Spec. Pap. 252. Chap. 4, pp. 77–110.

Plouffe, A. 2000. Surficial geology, Manson River, British Columbia. Geol. Surv. Canada, "A" Series Map, no. 1987A. One sheet.

Province of British Columbia. 2000. Forest road regulation. *Forest Practices Code of British Columbia Act*. Consolidated to July 19, 2000.

Siebert, S.A. 1987. A case history of a catastrophic erosion in the Coquitlam valley, B.C. B.Sc. thesis. Univ. B.C., Geol. Eng. Program., Vancouver, B.C.

U.S. Army Corps of Engineers. 1960. Runoff from snow melt, EM 1110-21406, Washington, D.C., Supt. of Documents.

Williams, M. 1966. The grand campus washout. UBC Alumni Chron. 20:9–11.

The Bourke Slide and Lessons for the Watershed Assessment Procedure

L. KALMAKOFF, B. GUY, AND D. NICOL

ABSTRACT

This paper presents a case study of a landslide and debris flow event in a community watershed in the Kootenays, and the lessons that can be learned for the watershed assessment process. The Bourke Creek watershed near Nelson, B.C., experienced a landslide and associated debris flow in April 1999 that impacted the domestic water supply for 33 households. The slide began at a switchback on the Sitkum Creek (Alpine) Forest Service Road and was attributed to the partial saturation of oversteepened and degraded road fill. The slide travelled down steep potentially unstable terrain for 70 m, became confined within a gully, and transformed into a debris flow. The debris flow entered Bourke Creek in a confined reach with a 40% gradient, continued downstream for another 375 m, and deposited in a large lobe at a location where the channel gradient decreased to 25%. Inspection of the slide 16 months later during a reconnaissance watershed assessment procedure (WAP) indicated that the slide track was vegetating and the domestic water supply had been re-established. The slide investigation highlighted that the WAP gives inadequate consideration to colluvial hazards. First, the WAP focuses on alluvial processes, not on a stream's sensitivity to colluvial processes and the associated hazards. Second, the WAP should identify consequences to downstream resources from colluvial hazards associated with roads and forest development to properly manage risk.

INTRODUCTION

The Bourke Creek watershed (Figure 1) is a 144-ha community watershed located approximately 15 km northeast of Nelson, B.C. The hillslopes are steep and directly coupled to the steeply confined channel, which has an average gradient of 30%. On April 24, 1999, a slide occurred off a switchback on the Sitkum-Alpine Forest Service Road (FSR). The slide initiated a debris flow within the steep channel, which resulted in scour of the stream banks, deposition of a large debris lobe, and the plugging of the community intake that supplies 33 households. The slide was assessed by Ministry of Forests personnel 5 days after the event, and a series of remedial efforts was undertaken to prevent further instability (Nicol 1999).

Subsequent inspection of the slide occurred during a reconnaissance watershed assessment in August 2000, approximately 1 year after the event

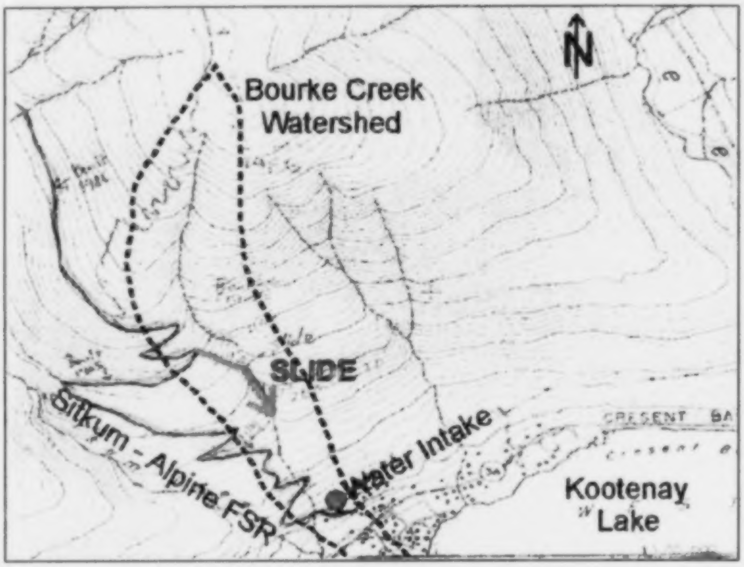


FIGURE 1 *Bourke Creek watershed showing the Sitkum-Alpine FSR and the community water intake.*

(Summit Environmental Consultants Ltd. [Summit] 2000). Remedial activities have been successful at stabilizing the slide. However, the quality of water in Bourke Creek is an ongoing issue, and residents do not use the water supply system to the same extent as before the slide event (J. Lintz, Bourke Creek Improvement District, pers. comm., 2001).

This paper reviews the initiation and behaviour of the slide, the remedial efforts, and the slide's current condition. It also discusses the current watershed assessment procedure (WAP) and the direction it provides for the identification of risks associated with colluvial hazards, using Bourke Creek as an example.

THE WATERSHED AND THE SLIDE

The Bourke Creek Community Watershed is characterized by steep slopes and a confined gully that contains the mainstem channel. The creek is approximately 4 km in length, with gradients ranging from 25 to 42%, dropping to 10% on the depositional fan at Kootenay Lake. Infrastructure on the fan includes residences, a community intake and water supply system, a highway, and a bridge. The consequences of upslope instability could therefore be severe. The channel was inspected in a 1996 channel assessment, in accordance with the applicable guidebook (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1995), and was identified as having the potential to transport debris flows to the fan, due to the channel-slope coupling, channel confinement, and steep gradient (Summit 1997). This judgement was made despite the lack of historical evidence of previous debris flows.

The Bourke Slide initiated on a steeply climbing forest road (Sitkum-Alpine FSR) that has several switchbacks located on potentially unstable terrain (as mapped by Banting Engineering Ltd. 1996). The slide initiated at a switchback at 1110 m elevation and created a 3–4 m high headscarp. It continued down the steep 100% slope, transforming into a debris flow (Figure 2a). Upon entering the confined Bourke Creek channel, where the gradient is 40%, the debris flow continued down for 375 m, scouring out a 20 m high swath of riparian and hillslope vegetation. At an elevation of 970 m, a slight widening of the gully and a decrease in gradient to 25% resulted in the deposition of the debris in a large lobe of sediment and large woody debris (Figures 2b and 3). The channel downstream of this location narrows again and has a gradient of 27%, and would have likely transported the debris directly to the fan and into domestic development had it not deposited at 970 m elevation. The estimated volume of the lobe is 2000 m^3. The deposition occurred approximately 750 m (along the channel) upstream of the water intake and domestic development, and serious damage did not occur. However, a large volume of fine sediment continued down the channel, plugging the intake and causing some property damage on the fan (J. Lintz, Bourke Creek Improvement District, pers. comm., 2001).

The slide and runout track was inspected 5 days after the event (Nicol 1999). Drainage conditions on the switchback were examined and traced upslope. There was no evidence that redirected road drainage contributed

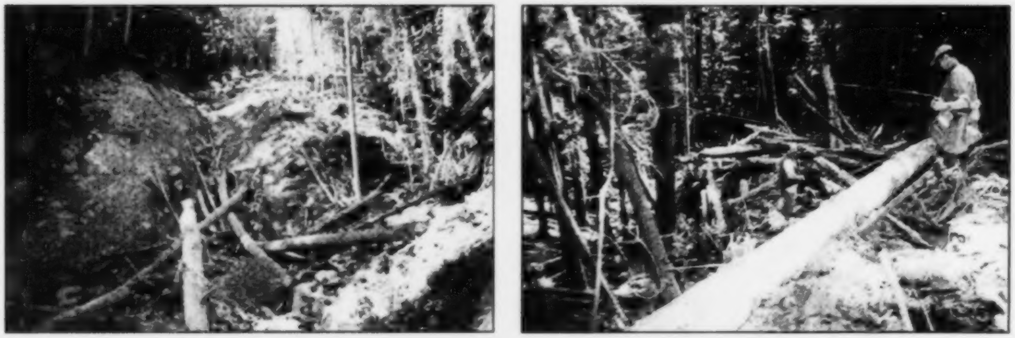


FIGURE 2 *The slide track (Figure 2a, left) and depositional lobe (Figure 2b, right) in April 1999.*

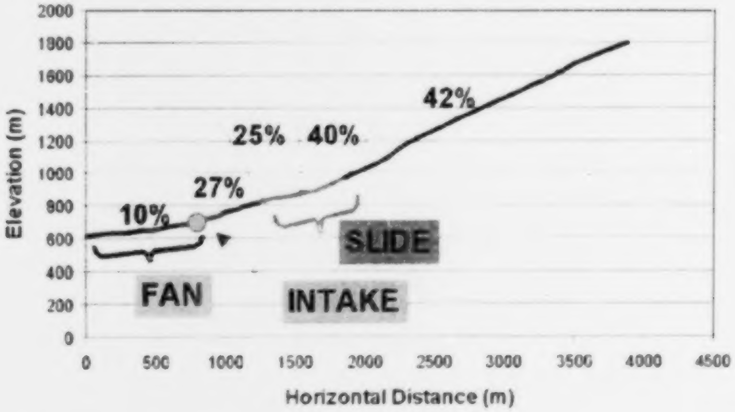
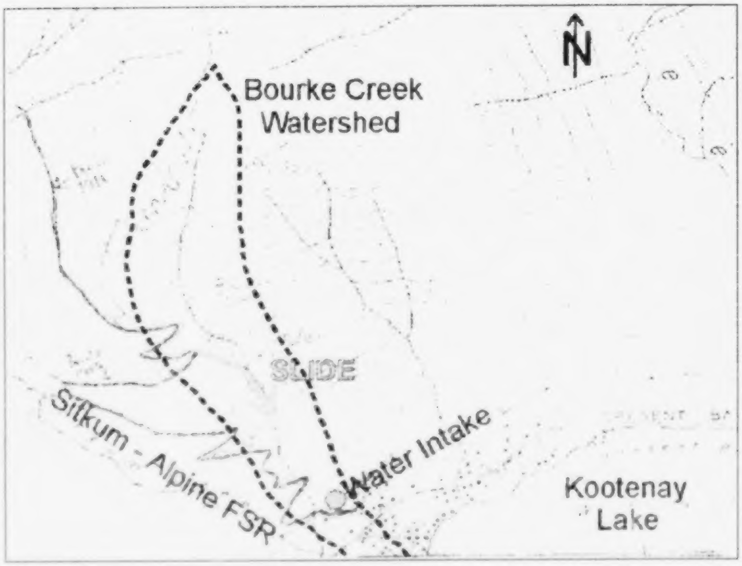


FIGURE 3 *Longitudinal profile of Bourke Creek.*



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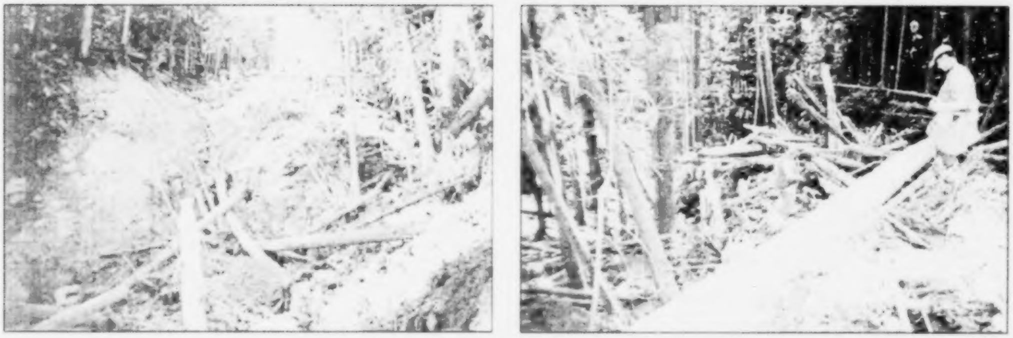


FIGURE 2 *The slide track (Figure 2a, left) and depositional lobe (Figure 2b, right) in April 1999.*

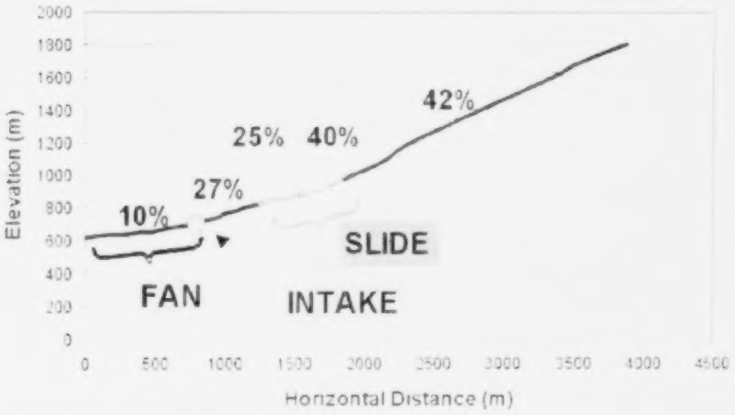


FIGURE 3 *Longitudinal profile of Bourke Creek.*

to the initiation of the slide; however, the next switchback upslope may have directed subsurface flow to the slide area. The most significant factors contributing to the slide were determined to be the presence of decaying organics within the road fill that had been placed either during the original road construction or during subsequent upgrades, and the downhill stresses that resulted from the oversteepened condition of the fill material. The slope failed when the fill became partially saturated from surface flow, subsurface flow, and snowmelt.

Recommendations were made for remedial efforts to stabilize the slide area. The remaining fill at the site was pulled back, the slide track and runout zone were hydro-seeded with a clover and grass mixture (Figure 4), and the switchback was reconstructed adjacent to the slide area to maintain vehicle access.

SLIDE CONDITION IN 2000

The area was subsequently inspected during a WAP (based on B.C. Ministry of Forests 1999) in August 2000, 16 months after the event (Figure 5). The seeding had established on approximately 60% of the exposed soil. Remedial activities have been successful at stabilizing the slide headscarp; however,

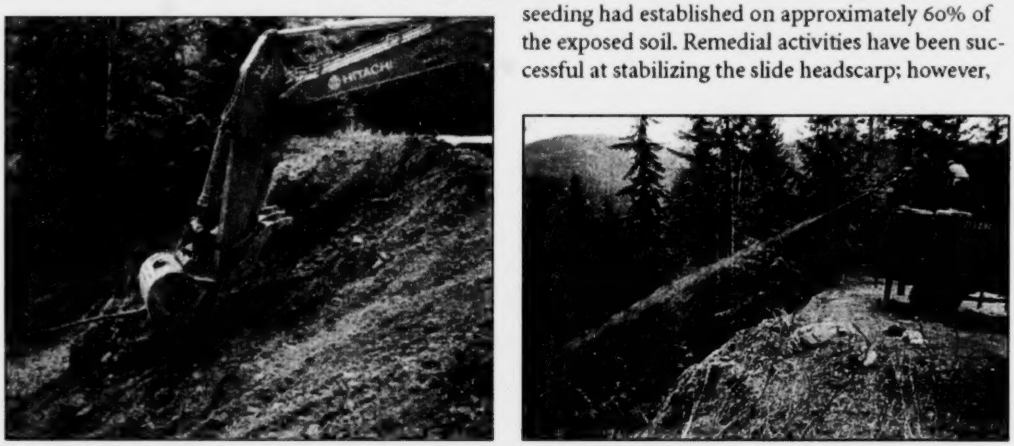
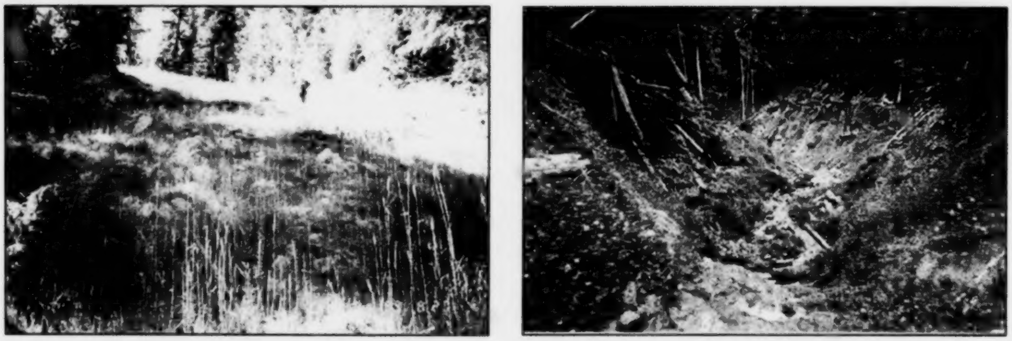


FIGURE 4 *Remedial efforts on the slide included pullback of the headscarp (left) and hydro-seeding with a grass and clover mixture (right).*



FIGURES 5 *Slide track (left) and Bourke Creek (right) in August 2000 showing growth of hydro-seeded grasses and clover.*

the scoured steep gully sides parallelling Bourke Creek continue to contribute some sediment to the channel. The headscarp was revegetating, and drainage structures along the road divert surface water and ditch flow away from the slide area.

The community water intake is again supplying water for domestic use; however, the quality of the water remains in question and a boil water advisory is in effect (J. Lintz, Bourke Creek Improvement District, pers. comm., 2001). Many of the local water users still choose to drink bottled water. Fine-textured overbank sediment deposited during the debris flow remains on the banks downstream of the debris lobe, and becomes entrained in the water during high flows. As a result, the intake requires cleaning several times each year (J. Lintz, Bourke Creek Improvement District, pers. comm., 2001).

THE CURRENT WATERSHED ASSESSMENT PROCEDURE

Consideration of the severe potential consequences of the slide led to an examination of how the current WAP guides an assessor to identify colluvial hazards, particularly in watersheds that have no historic evidence of debris flows, such as Bourke Creek.

The risk of colluvial processes can be difficult to identify. However, because such processes may pose significant risks to life and property, it is important that the risks be identified correctly. Colluvial processes are those that are dictated by gravity. The most common types include landslides, debris flows, rockfall, and soil creep. Table 1 presents the general slope gradient categories that dictate the behaviour of debris flows. Other factors such as confinement, water content, drainage conditions, and soil and root cohesion also affect the behaviour of debris flows; however, we present slope as a guiding factor because it is a simple measurement that can be made in the field. Fannin and Rollerson (1993) and Millard (1999) discuss the initiation and behaviour of debris flows in greater detail.

The focus of the current (1999) version of the WAP is to examine the present state of the watershed and identify characteristic processes based on historical evidence of their occurrence. It provides more flexibility in methods and interpretation than does the original (1995) guidebook, which used a series of map measurements to produce "hazard scores" for a number of watershed variables.

In the current (1999) WAP guidebook, the "qualified professional" is guided through four main steps. The first is an assessment of the harvesting history within the watershed and the potential for previous harvesting to have affected the channel network. The second includes a reconnaissance channel

TABLE 1 *Slope thresholds governing debris flow behaviour*

	Slope (%)
Initiation	≥ 40
Transportation	≥ 27
Deposition	21 (±10)

Note: Based on a Type II event, defined as a single event initiating in a gully or on an open slope before entering a gully (Fannin and Rollerson 1993) assessment (RE-CAP) that is intended to determine the characteristics of the channel network, including morphology, evidence of disturbance, stability, and sensitivity to future changes. The third is a sediment source survey (SSS) that inventories the existing sources of sediment to the channel network, and assesses their stability and rate of sediment supply. The final step is a riparian assessment that examines the condition of the riparian vegetation along the channel network to identify historical disturbance and impacts on the channel. Of these four steps, only the RE-CAP and the SSS have the potential scope to assess colluvial hazards. However, these portions of the WAP guidebook provide only a weak reference to colluvial hazards, and do not address the situation where historic colluvial activity cannot be used to predict a hazard.

The RE-CAP consists of an office review of maps and aerial photos, followed by a ground survey of reaches suspected to be sensitive or having suffered disturbance. The focus is on the channel itself and its fluvial conditions. The guidebook suggests that an assessor discuss the mapped features, channel types, disturbance, flood distribution, channel stability, and any noted alluvial hazards, and is less focused on channel sidewall stability or the stability of hillslopes coupled to channels. In this context, the alluvial hazards mean those related to overbank flooding or altered channel pattern, such as avulsions. The classification for channel type is focused primarily on the alluvial characteristics of the channel, rather than the governing processes that may dictate sediment transport, such as hillslope colluvial processes. In addition, the assessor is guided to look for historical evidence of any activity within the area to provide an indication of existing hazards. With a lack of such historical evidence, such as in the case of Bourke Creek, the assessment of colluvial hazards may be incomplete.

The SSS is intended to assess the existing sediment sources within the watershed, and note their delivery potential to the channel network, sedimentation rate, and type and origin of disturbance. The guidebook briefly advises the assessor to identify any terrain types of special concern; however, this is the only reference to overall concepts of mass movement. Similar to the RE-CAP, the SSS focuses on existing conditions rather than potential future conditions.

The current (1999) WAP guidebook indicates that references to additional information such as terrain stability mapping, geotechnical reports, and information on *known* debris flow areas should be made during a watershed assessment. However, if the information is not available, or if it exists at too crude a scale, such information may be of limited use. In addition, the importance of these issues is not highlighted to the extent that it should be, considering the potential consequences associated with debris flows. Therefore, it is possible that a watershed assessment conducted according to the current WAP guidebook could easily miss the identification of colluvial processes.

In addition to these four steps, the assessor is guided to provide information on a host of other issues, such as unstable terrain and known debris flow hazard areas (B.C. Ministry of Forests 1999, p. 6) that may be related to the target watershed. The importance of these additional issues is not highlighted to the extent that it should be, considering the consequences of some of the information, such as the risk of debris flows. Therefore, such issues may not be given adequate consideration by the assessor. Futhermore, a watershed assessment conducted according to the guidance provided by the current WAP guidebook could miss the identification of colluvial processes.

RECOMMENDATIONS

We have two recommendations that will make the watershed assessment process more comprehensive. The first is to focus the investigation on the dominant processes within the watershed, because the WAP is not explicit regarding this. In-channel sediment transport mechanisms should be accurately identified based on channel type and bedload. Factors relevant to colluvial processes such as slope, channel confinement, hillslope coupling, and water and sediment supply should be identified. The inventory of existing sediment sources should be expanded to include hazards for events that possibly have not occurred in the past. Bourke Creek showed no signs of historic instability before 1999. However, due to its highly confined gully with steep slopes, and its source of sediment and water, the creek's potential for debris flows was recognized in the 1996 WAP. In addition, the road switchbacks upslope of the creek posed a hazard with potentially serious downstream consequences. Note that although the 1996 investigation identified this hazard in Bourke Creek, it was not done by following the 1995 guidebook (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1995) that applied at that time.

The definition of qualified professional in the current (1999) WAP guidebook emphasizes experience in hydrology, and mentions experience in slope processes and fluvial geomorphology only secondarily. We feel that the WAP guidebook understates the importance of knowledge of geomorphic processes in its discussion of qualified professionals.

Second, we feel that the channel classification system (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1996) suggested in the 1999 WAP guidebook is too narrowly focused to assess channel types dominated by colluvial processes. The WAP system includes several categories of alluvial channels, and we suggest the addition of bedrock channels and colluvial channels. Both of these channel types are described in the system presented by Montgomery and Buffington (1997). There is an implicit link between colluvial behaviour of the hillslope and channel type presented in Appendix 2 of the *Channel Assessment Procedure Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1996). However, this link should have been more strongly presented within the text of the WAP guidebook, and included in the channel classification system in Appendix 3.

CONCLUSIONS

The current (1999) watershed assessment procedure fails to explicitly direct an assessor to consider some important aspects of terrain characteristics in watersheds affected by colluvial processes. It is particularly a concern in small, steep basins. The assessor must consider the downstream consequences of a colluvial event such as a debris flow, and investigate upslope hazards that may exist. Because of the lack of prominence given to this issue within the WAP guidebook, the assessor may fail to take the initiative to seek evidence in the field. An individual with experience in hillslope and fluvial processes is best suited to determine the dominant physical processes operating within the watershed, and the WAP should be clearer that these skills are of primary, rather than secondary, importance. Proper identification of colluvial hazards is important because colluvial events have the potential to impact not only aquatic and terrestrial resources, but also to put lives, private property, and infrastructure at risk.

REFERENCES

Banting Engineering Ltd. 1996. Detailed terrain stability report: TSIL 'B', Sitkum Creek Watershed. Prepared for Slocan Forest Products, Slocan Division. Slocan, B.C.

British Columbia Ministry of Forests. 1999. Watershed assessment procedure guidebook. 2nd ed., Version 2.1. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

British Columbia Ministry of Forests and B.C. Ministry of Environment, Lands and Parks. 1995. Interior watershed assessment procedure guidebook (IWAP) – level 1 analysis. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

British Columbia Ministry of Forests and B.C. Ministry of Environment, Lands and Parks. 1996. Channel assessment procedure guidebook. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

Fannin, R.J. and T.P. Rollerson. 1993. Debris flows: some physical characteristics and behaviour. Natl. Res. Counc. Can., reprinted from Can. Geotech. J. 30(1):71–81.

Millard, T. 1999. Debris flow initiation in coastal British Columbia gullies. B.C. Min. For., Vancouver Forest Region, Nanaimo, B.C. For. Res. Tech. Rep. 2. Available at: http://www.for.gov.bc.ca/VANCOUVR/research/georeports/ tr002.pdf

Montgomery, D.R. and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109(5):596–611.

Nicol, D. 1999. Letter report to Mr. Ken Haynes of the Kootenay Lake Forest District re: Bourke Creek Landslide. May 6, 1999.

Summit Environmental Consultants Ltd. (Summit). 1997. Sitkum Creek: level 1 Interior watershed assessment procedure. Prepared for Slocan Forest Products Ltd., Slocan Division. Vernon, B.C.

———. 2000. Watershed assessment: Sitkum, Bourke, and Clayton Creek. Draft report. Prepared for Slocan Forest Products Ltd., Slocan Division. Slocan, B.C.

Terrain Stability Problems and Four Main Types of Landslide-Prone Materials in the Prince George Forest Region, British Columbia

ZHONGYOU LU, MARC ST. ARNAUD, AND TERRY ROLLERSON

ABSTRACT

Four terrain stability mapping projects in the Mackenzie, Dawson Creek, and Fort St. James Forest Districts and a number of terrain stability field assessments in the Prince George, Dawson Creek, Fort St. John, Fort St. James, and Mackenzie Forest Districts were carried out. Results indicate that the major terrain stability problems in the Prince George Forest Region are concentrated in four main types of landslide-prone surficial materials: (1) glaciolacustrine and lacustrine deposits; (2) sedimentary rocks of Cretaceous and Jurassic ages (interbedded sandstone, shale, and mudstone) and particularly metamorphic rocks (phyllite, slate, schist, phyllitic limestone, and serpentinite); (3) clayey morainal deposits; and (4) colluvial deposits produced from the rocks noted above. Different types of terrain stability problems occur in different types of surficial materials. For example, earth slides, earth flows, and serious surface erosion occur in glaciolacustrine and lacustrine deposits; rock topples, rockslides, rockfalls, and consequent debris flows occur in certain lithologies; debris slides occur in clayey morainal deposits; and debris slides and debris flows are common in colluvial deposits produced from the rocks noted above. Most terrain stability problems in the Prince George Forest Region have occurred in these four types of landslide-prone materials. A sound understanding of the geotechnical properties of these materials and a clear picture of the distribution of these materials will greatly improve forest management in the region.

INTRODUCTION

The Prince George Forest Region includes the Fort Nelson, Fort St. John, Dawson Creek, Mackenzie, Fort St. James, Vanderhoof, Prince George, and Robson Valley Forest Districts and has an area of approximately 280 000 km^2. The region is located mainly within the following physiographic units: the Interior System (Central Plateau and Mountain Area, Rocky Mountain Trench, and Southern Plateau and Mountain Area); the Eastern System (Mackenzie Mountain Area and Rocky Mountain Area of the Canadian Cordillera); and the Interior Plains (Alberta Plateau) (Holland 1964).

In the Prince George Forest Region, five major geologic units (Holland 1964) are present: (1) flat or gently dipping Cretaceous sedimentary rocks in the Alberta Plateau System, including the Fort Nelson Lowland Division; (2) closely folded and faulted Mesozoic sedimentary rocks in the Rocky Mountain Foothills Division; (3) closely folded and faulted Palaeozoic sedimentary and metamorphic rocks in the Eastern System of the Canadian Cordillera (Mackenzie Mountain Area and Rocky Mountain Area), including the Rocky Mountains and the Rocky Mountain Trench covered by thick sediments at present; (4) closely to gently folded and faulted Mesozoic sedimentary and volcanic rocks in the Central Plateau and Mountain Area, including the Skeena Mountains and the Omineca Mountains divisions; and (5) flat or gently dipping volcanic rocks with limited granite intrusions in the Southern Plateau and Mountain Area, including the Interior Plateau, Nechako Plateau, and Fraser Plateau divisions.

The lithology and structure of bedrock have determined the frame of landscape and drainage patterns, and have a very strong influence on the textures of surficial materials and terrain stability characteristics such as the particular types, sizes, and other characteristics of slope movements in the region.

The region experienced several glaciations during the Pleistocene (Ryder 1978). Most likely, only the latest glacial deposits are widely seen on the ground at present. Almost the whole region was covered by the Cordilleran ice sheet from southwest or west about 15 000 years ago, except for the Alberta Plateau, which was covered by the Keewatin ice sheet from the east, and the north Rocky Mountains, which were covered by a local ice cap. Morainal, glaciofluvial, and glaciolacustrine deposits are widespread in the region.

Generally, the whole area of the Prince George Forest Region has a typically continental climate: long cold winters and short cool summers with moderate precipitation. Mean annual temperatures range from −1.3 to 3.3°C. The annual range of temperature is between 25 and 40°C. Bright sunshine hours are in the range of 1755–2130 (Schaefer 1978). Therefore, weathering, especially physical weathering, has played an important role in bedrock decomposition.

All bedrock geology, tectonic history, glacial history, and climate have directly or indirectly determined the landscape frame, the textures, and the geotechnical properties of surficial materials, as well as the characteristics of potential slope movement in the region.

This paper provides examples of the main types of terrain stability problems and related landslide-prone surficial materials in the Prince George Forest Region. The analyses and conclusions reached by this paper are based on local knowledge and on limited data that we have obtained from terrain stability mapping and site assessments carried out in the region. The understanding presented in this paper may be applicable to neighbouring areas, but limitations are obvious because of differences of geological setting.

Our nomenclature for landslides follows Cruden and Varnes (1996).

The results of four terrain stability mapping projects (Terrain Survey Intensity Level C at a scale of 1:20 000) in Mackenzie, Dawson Creek, and Fort St. James Forest Districts and a number of terrain stability site assessments in the Prince George, Dawson Creek, Fort St. John, Fort St. James, and Mackenzie Forest Districts indicate that the major terrain stability problems in the Prince George Forest Region are concentrated in four main types of surficial materials:

- glaciolacustrine and lacustrine deposits;
- sedimentary rocks (interbedded sandstone, mudstone, and shale) of Cretaceous and Jurassic ages and particular metamorphic rocks (phyllite,

slate, schist, phyllitic limestone, and serpentinite);

- clayey morainal deposits; and
- colluvial deposits produced from the rocks noted above.

TERRAIN STABILITY PROBLEMS IN GLACIOLACUSTRINE DEPOSITS

During deglaciation, large volumes of meltwater were released as the ice melted. In many places throughout northern British Columbia, ice marginal lakes were formed about stagnant masses of ice lying in valleys. Glaciolacustrine sediments deposited in the ice-dammed lakes remained as terraces and abandoned deltas when water levels lowered. Many such lakes were ephemeral, and disappeared when the ice blocks finally melted. As a result, glaciolacustrine deposits cover a substantial portion of northern British Columbia (Holland 1964; Ryder 1978). These deposits comprise some of the most landslide-prone surficial materials in the area.

Numerous landslides occurring within glaciolacustrine deposits or along their upper surfaces have caused serious problems for transportation corridors, city development, agriculture, and the forest industry in northern British Columbia. Earth slides and earth flows are the most common landslide types, especially in silty and clayey glaciolacustrine deposits. Earth slides and earth flows may very often combine to form an earth slide–flow complex. Earth flows developed within the displaced material may occur concurrent with earth slides, or later.

Because the sediments deposited in glacial lakes are derived mainly from the erosion products of local bedrock, as well as previous sediments in the area, the textures of glaciolacustrine deposits are dependent mainly on the particles the local bedrock can produce. The characteristics of the bedrock in the study area correspond well with the textures of different glaciolacustrine deposits.

Three basic types of glaciolacustrine deposits have been recognized in the study area: sandy, silty, and clayey. These different types of glaciolacustrine deposits pose different terrain stability problems (Lu et al. 1998).

Terrain Stability Problems in Sandy Glaciolacustrine Deposits

Typical sandy glaciolacustrine deposits have been found in the Herrick Creek drainage and the Government Creek drainage, Prince George Forest District.

The glaciolacustrine deposits in the Herrick and Government Creek drainages consist of mainly loose, uncemented fine sand (50–70%), silt (30–50%), and minor clay (< 2%). These sediments are very vulnerable to surface erosion: sheet erosion and gully erosion. The serious surface erosion problems along the main logging road built in Herrick Creek provide good examples of these processes. Following sheet erosion, different sizes of rills and gullies have formed in the area. Gully erosion removed more sediment from upslope areas and transported them into the mainstream. Over time, the fine sediments from small gullies and upper slopes have accumulated in larger gullies. In the Herrick Creek drainage, large gullies received huge quantities of fine sand and silt, which formed very wide (up to 60 m) and gentle (< 2°) gully bottoms covered by dense vegetation.

Figure 1 shows the sandy glaciolacustrine deposits in Government Creek and the results of surface erosion. Photographs taken on April 23 and May 21, 1996, respectively, provide good examples of surface erosion in sandy

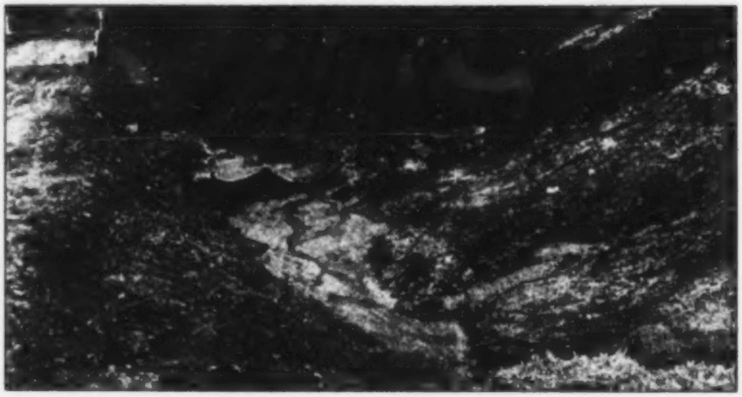


FIGURE 1 *This photo was taken April 23, 1996. Note that the silt fence was half-filled. In less than 1 month, on May 21, 1996, a further 0.6–0.7 m of fine sand and silt had accumulated behind the silt fence.*

glaciolacustrine deposits. Within 1 month, the silt fence was filled to a depth of 0.6–0.7 m with fine sand and silt. The photograph demonstrates how active and serious surface erosion in sandy glaciolacustrine deposits in the area can be. The geotechnical problems in this type of deposit are more often surface erosion than landsliding.

Sometimes, a clay-rich silt layer may be present at the bottom or the lower portion of sandy glaciolacustrine deposits, for example in the Herrick Creek valley. Then, earth slides may occur. The slopes consisting of sandy sediments may move along the weak clay-rich silt layer.

Terrain Stability Problems in Silty Glaciolacustrine Deposits

Typical silty glaciolacustrine deposits are found in the Akie River and Pesika Creek drainages, Mackenzie Forest District.

The glaciolacustrine deposits in the Akie River and Pesika Creek valleys have similar textural and depositional characteristics. These widely distributed deposits consist of weakly to moderately cemented silt (60–85%), sands (10–35%, usually forming sand lenses), and minor clay (5–10%). Very gently inclined bedding (≤ 6° dipping towards the centre of the previous drainage), laminae, and varves are well developed within these silty glaciolacustrine deposits.

Numerous earth slides have been observed in glaciolacustrine deposits in the Akie River and Pesika Creek valleys (Figure 2). The surfaces of rupture of earth slides follow the bedding planes of the glaciolacustrine deposits, and the main scarps follow steeply dipping joints.

Weak, gently dipping bedding planes of the glaciolacustrine deposits often provide potential surfaces of rupture, especially when they are fully saturated. These pre-sheared bedding planes may easily reach the residual strengths of the materials. The steeply dipping joints provide the boundaries of the earth slides. When lateral support is removed by stream erosion, substantial glaciolacustrine deposits can move out rapidly along pre-sheared bedding planes.

Often, earth slides may change into earth flows concurrently when glaciolacustrine deposits move a certain distance and/or become substantially saturated. After sufficient water enters the loose sediments, earth flows may develop in displaced materials and form slurry. All these earth flows have moved slowly along the previous ground surface (Figures 3 and 4). The

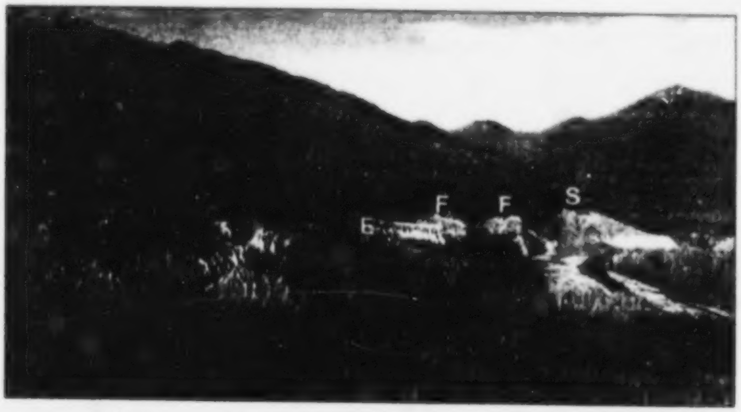


FIGURE 2 *Glaciolacustrine deposits in the lower Akie River. Note the flat top surface, serious gully erosion (E), the large earth slide (S), and earth flows (F) on the right side of the photo.*

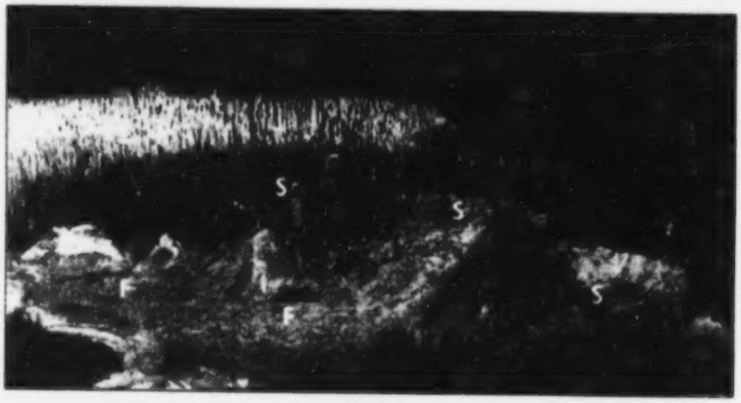


FIGURE 3 *An earth slide (S) and earth flow (F) complex in glaciolacustrine deposits in the Pesika Creek valley.*

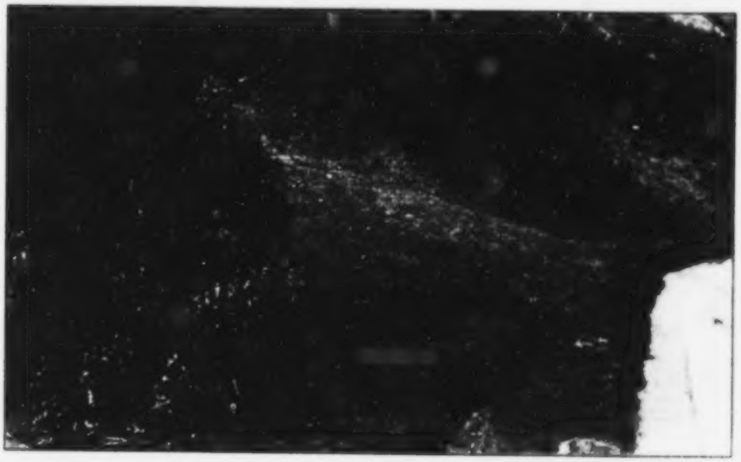


FIGURE 4 *A large earth slide-flow complex in the Ospika River, Mackenzie Forest District.*

displaced materials are near full saturation and form slurry. The friction angle at the bottom of these earth flows may reach values as low as 5–7° along the shear surface between the slurry and the ground surface.

Earth falls have also been observed in the thick glaciolacustrine deposits in the Akie River valley. The individual layer of the glaciolacustrine deposits is 1.5 m thick. These sediments are very well cemented by calcite. Stress release–induced, near-vertical joints are well developed, especially at corners where two perpendicular stress release joints cut deeply into these deposits (Figure 5). These stress release joints cut the calcareous cemented sediments into columns. When toe support is removed or water/ice pressure accumulates behind the columns, earth falls take place. The columns break into large blocks when free falling or bouncing, and move rapidly down the slopes. Cementation of these deposits plays an important role in column and block formation. Discontinuities, joints, and bedding planes play another important role in the formation of columns and blocks and eventual earth falls.

Significant surface erosion, especially gully erosion, also occurs on exposed surfaces in these deposits in the Akie River and Pesika Creek valleys.

Terrain Stability Problems in Clayey Glaciolacustrine Deposits

Clayey glaciolacustrine deposits cover a large portion of the Prince George Forest Region. These deposits have been found in the City of Prince George and its surroundings, in the Peace River area in British Columbia, in the Fort Nelson Forest District, and along the Fraser River. These deposits consist of clay (25–45%), silt (35–55%), and fine sand (5–10%). Bedding, laminae, and varves are well developed. Most of the bedding planes in these clayey glaciolacustrine deposits are pre-sheared. The friction angle along these bedding surfaces is very close to the residual friction value for these materials. As a

FIGURE 5 *An earth fall area in cemented glaciolacustrine deposits in the Akie River valley. Note that two sets of near-vertical stress release joints (1 and 2), perpendicular to each other and near horizontal bedding planes, cut the sediments into slim columns or blocks.*

result, earth slides have widely occurred and are the dominant type of slope stability problem in these deposits. Surface erosion in these deposits is minor compared with surface erosion in sandy and silty glaciolacustrine deposits.

The surfaces of rupture of most earth slides in clayey glaciolacustrine deposits are deep seated. The landslide on Highway 16 at the east boundary of the City of Prince George is one of those kinds of slides (Figure 6). At this location, the glaciolacustrine deposit is overlain by till and a glaciofluvial deposit composed of gravels and sands. The surface of rupture is located along a weak, gently dipping bedding plane in the glaciolacustrine deposit. The front part of the slide moved out onto the highway at the toe of the cutslope. The slide is still active, especially in wet seasons. Highway maintenance is required every year. The east side of the cutslope has a longer history of movement. Surface drainage systems do not appear to be working well. The main part of the surface of rupture of this slide is at least 20 m deep.

Note that some landslides occur in complex stratigraphy: glaciolacustrine deposits overlain by coarse- to medium-textured materials, either glaciofluvial or morainal deposits. As the major part of the material displaced in the landslide is glaciofluvial or morainal deposits on the ground, sometimes it may be interpreted as a debris slide in glaciofluvial or morainal deposits. This is incorrect because the main part of the surface of rupture develops along the top surface of glaciolacustrine deposits or on the bedding planes within glaciolacustrine deposits. The initiation of the landslide depends entirely on the geotechnical properties of the glaciolacustrine deposits rather than the coarse- to medium-textured glaciofluvial or morainal deposits. The landslide on Highway 16 at the east boundary of the City of Prince George provides a good example of this type. The surface of rupture follows along the bedding planes within glaciolacustrine deposits that are overlain by glaciofluvial deposits.

A series of earth slides has been found in the clayey glaciolacustrine deposits on the north bank of the Fraser River near Hixon, B.C. The surfaces of rupture of these earth slides have developed along weak and gently dipping bedding planes. The main scarps have followed steeply dipping joints

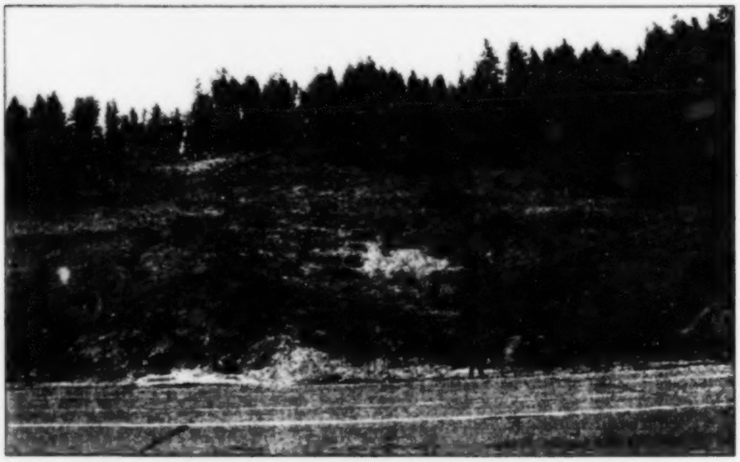


FIGURE 6 *A deep-seated landslide in glaciolacustrine deposits overlain by till and glaciofluvial deposits on Highway 16, at the east boundary of Prince George.*

(Figure 7). These earth slides have characteristics similar to the "Big Slide" and its neighbouring slides on the east side of the Fraser River near Quesnel (Lu et al. 2000).

Numerous deep-seated earth slides in the Peace River area in British Columbia have characteristics similar to the large landslides recognized in the western Peace River Lowland, Alberta (Cruden et al. 1993; Cruden et al. 1997; Lu et al. 1998). The typical examples are the earth slides closely distributed along the north bank of the Peace River near Taylor (Figure 8) and the 1973 Attachie slide near Fort St. John (Evans et al. 1996).

Glaciolacustrine deposits cover a large portion of the Prince George Forest Region. Sandy, silty, and clayey deposits are the three basic types recognized. Each type has special slope stability problems. Surface erosion dominates in sandy glaciolacustrine deposits. The silty glaciolacustrine deposits are the most hazardous materials in the region. Surface erosion, earth slides, and earth flows are widespread. Deep-seated earth slides and subsequent earth

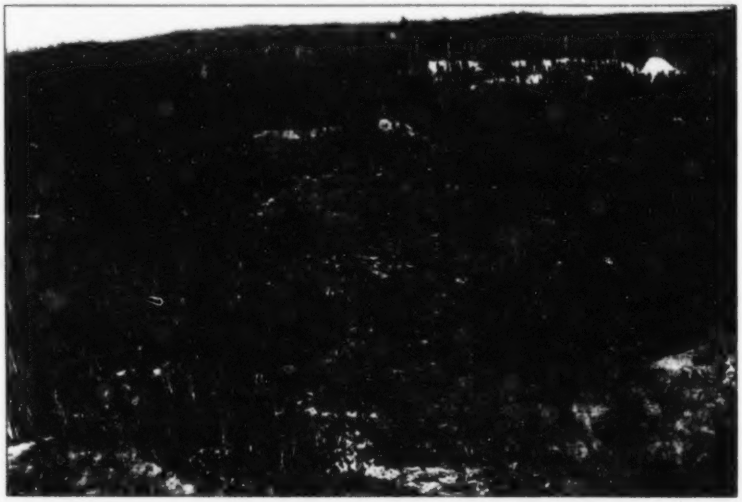


FIGURE 7 *Details of a large earth slide on the north bank of the Fraser River near Hixon, B.C. The slides moved rapidly in the early stage and then slowed down.*

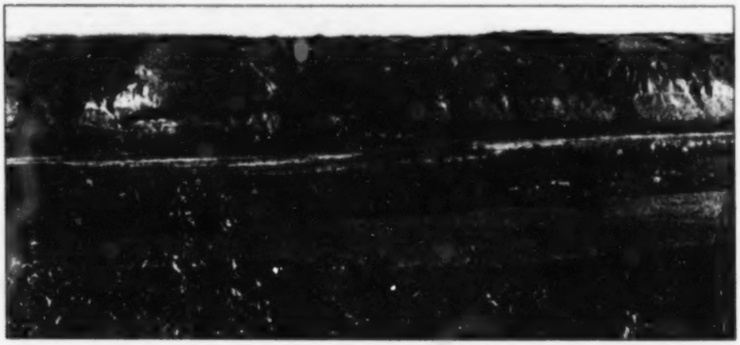


FIGURE 8 *Large, deep-seated earth slides on the north side of the Peace River, Taylor, B.C.*

flows are the dominant slope stability problems in clayey glaciolacustrine deposits, while surface erosion is a minor problem.

The following summarizes our findings about glaciolacustrine deposits:

- Glaciolacustrine deposits, the most important landslide-prone material in the Prince George Forest Region, can be naturally divided into three subtypes: sandy, silty, and clayey. Each subtype has its dominant terrain stability problems.
- In sandy glaciolacustrine deposits, the dominant terrain problems are surface erosion.
- In silty glaciolacustrine deposits, dominant terrain problems are earth slides, earth flows, and surface erosion.
- In clayey glaciolacustrine deposits, dominant terrain stability problems are deep-seated earth slides and earth flows.
- The surfaces of rupture of earth slides in glaciolacustrine deposits often develop along weak, pre-sheared bedding planes. The friction angle along fully saturated bedding planes is very close to the dip angle of the bedding. Sets of near-vertical joints often provide lateral boundaries for earth slides.
- Water penetration into displaced glaciolacustrine deposits transforms them into fully saturated slurry and forms earth flows. These earth flows occur either concurrently with earth slides or later.

TERRAIN STABILITY PROBLEMS IN PARTICULAR SEDIMENTARY AND METAMORPHIC ROCKS

Rockslopes may be unstable because of bedrock lithology and structure within the rock mass. Bedrock lithology and structure usually determine the tendency for rockslope movement, and the type and the characteristics of landslides: size, activity, velocity, and subsequent movement. In the Prince George Forest Region, many landslides have occurred within three types of bedrock: flat-lying or gently dipping interbedded sedimentary rocks of Cretaceous Age in the Interior Plains, Fort St. John, and Fort Nelson Forest Districts; closely folded or steeply dipping interbedded sedimentary rocks of Jurassic to Lower Cretaceous Age in the Rocky Mountain Foothills, west portion of Fort St. John and Dawson Creek Forest Districts; closely folded, faulted, and foliated metamorphic and meta-sedimentary rocks of Palaeozoic Age in the north Rocky Mountains, Mackenzie Forest District; and folded and faulted metamorphic rocks of chiefly Mesozoic Age in the Omineca Mountains, Fort St. James Forest District. Terrain stability problems are common on the rockslopes in these areas. Each area has special types of terrain stability problems, depending on the bedrock lithology and structures.

Terrain Stability Problems in Flat-Lying or Gently Dipping Interbedded Shale, Mudstone, and Sandstone of Cretaceous Age

Landslides in Cretaceous interbedded sandstone, mudstone, and shale in the Fort St. John Forest District are discussed in Lu and St. Arnaud (2002). Only the main points are reviewed here.

Surfaces of rupture of the rockslides in Cretaceous rock often follow gently dipping bedding planes, especially bedding planes in shale. The dip angle of major rupture surfaces can be as gentle as 5°. The shear strength along the bedding planes in shale is substantially reduced when fully saturated. Many slope failures occur along weak shale layers or bedding planes. The lateral boundaries of these rockslides generally follow steeply dipping joints.

River downcutting plays a very important role in the initiation of these rockslides. Without the exposure of weak bedding planes along stream escarpments, these large, deep-seated rockslides would not occur. Groundwater has played an important role in the initiation of these rockslides by reducing shear strength along potential rupture surfaces.

Unlike the deposits of other types of rockslides, (e.g., those developed in limestone, quartzite sandstone, and quartzite in the Rocky Mountains in both Alberta and British Columbia), the landslide deposits formed by these types of rockslides and their weathering products in the study area may move again and again. Debris slides and debris flows are widespread on these materials in the Fort St. John Forest District. As a result, the landslides occur in groups and move repeatedly in the study area.

Terrain Stability Problems in Closely Folded or Steeply Dipping Interbedded Sandstone, Mudstone, and Shale of Jurassic to Lower Cretaceous Age in Rocky Mountain Foothills: Dawson Creek and Fort St. John Forest Districts

The west portion of Fort St. John and Dawson Creek Forest Districts is located in the Rocky Mountain Foothills. The area is underlain by closely folded or steeply dipping interbedded sedimentary rocks: sandstone, mudstone, and shale of Jurassic to Lower Cretaceous age (Figure 9). Well-developed joints cut the rock mass into different-sized blocks. Among these joints, one set of shear joints, perpendicular to the bedding planes, provides the most important boundary to slope movement: rockfalls and rockslides.

The bedrock in the area usually forms two types of slopes: dip slopes and scarp slopes. The weak shale layers and bedding planes have very low strength when fully saturated, almost no cohesion, and a low friction angle of 5–10°. When the potential surface of rupture is exposed at the toe of dip slopes by either incision or excavation, rockslides may occur. On the other side of hills, rockfalls occur on the scarp slopes. These rockslides and rockfalls are very common in the Pink Mountain area, Fort St. John District; the Sukunka River; and the Murray River valleys, Dawson Creek Forest District. Furthermore, as the displaced materials contain substantial fine particles (silt and clay), these fine particles may be carried downward by groundwater and

FIGURE 9 *Rock topples in steeply dipping interbedded sedimentary rocks of Jurassic Age in the Sukunka River valley, Dawson Creek Forest District. Note the overturned rock on the top part of the slope.*

accumulate at depth to form a new zone of weakness. Debris slides and subsequent debris flows may then occur at this zone of weakness.

Terrain Stability Problems in Metamorphic Rocks

Serious terrain stability problems were found in the northern Rocky Mountains underlain by closely folded, faulted, and foliated metamorphic and meta-sedimentary rocks of Palaeozoic Age, most likely Cambrian to Devonian. Numerous rock topples, rockfalls, rockslides, and subsequent debris slides and debris flows were observed in the area underlain by near-vertical metamorphic and slightly metamorphosed sedimentary rocks (i.e., phyllite, slate, schist, and phyllitic limestone) in the Akie River and Pesika Creek valleys, Mackenzie Forest District. A large number of rockslides and rockfalls were also found in the area underlain by serpentinite of chiefly Mesozoic Age in the Omineca Mountains area, Fort St. James Forest District. This paper provides some examples of terrain stability problems in the Akie River and Pesika Creek valleys.

The bedrock in the study area is closely folded and faulted about a northwest-trending axis and is cut by southwest-trending secondary faults. The geologic structure strongly controlled the development of the topography and the drainage pattern in the study area. The bedrock lithology and discontinuities have significantly determined the terrain, surficial materials, and slope stability problems in the area. The orientations of the bedding planes or foliations are fairly consistent in the study area. They strictly follow the fold axis striking northwest and dipping northeast or southwest at a very high angle (i.e., 70–85° to nearly vertical) (Figure 10) (Lu et al. 1998).

Three to four sets of joints were observed and measured in the field (Figure 11). They are also fairly consistent. Almost all of them are perpendicular to sub-perpendicular to the bedding or foliation and with each other at distinctive dip angles: either nearly vertical or nearly horizontal.

The steeply dipping bedding planes and/or foliation, together with the steeply dipping joints, cut the bedrock into thin columns, pieces, and blocks. The gently dipping shear joints (dipping at angles of 10–30°), perpendicular or sub-perpendicular to bedding planes or foliations, provide surfaces of separation, allowing the columns, pieces, and blocks to topple and break (Figure 12).

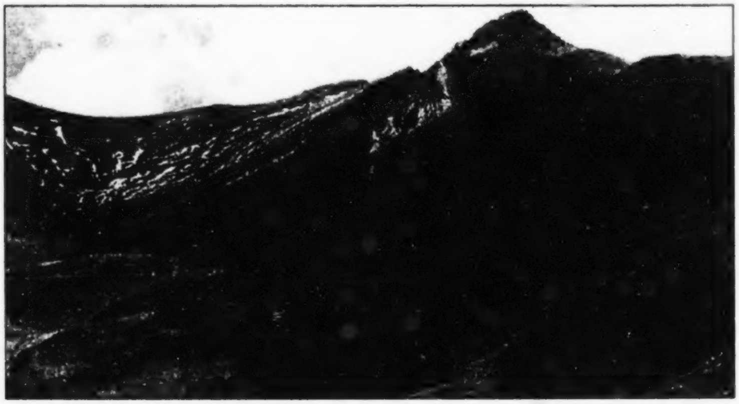


FIGURE 10 *Natural bedrock exposures showing almost vertical bedding and foliations, running northwest to southwest in the Akie River valley.*

The dominant natural slopes in the study area run northwest to southeast, dipping to either northeast or southwest at 45–80°. The strikes of the bedding planes or foliations are sub-parallel to parallel to the slopes. Common topples, external force-induced topples, and secondary topples (Goodman and Bray 1976; Cruden et al. 1993) were widely observed in the field.

Rock toppling is the most important type of landslide in phyllite, phyllitic limestone, slate, and phyllitic slate in the study area. It is also the starting point of a slope movement chain: rock topple → debris slide → debris flow → colluvial/alluvial fan → debris slide at the toe of the fan where the fan impinges on a stream channel (Figure 13).

Topples in the study area provide good examples of how rock topples progressively expand in size when the first topple is uncontrolled. At least four stages of topple development, from shallow to deep, are recognizable on the slopes. The movement of each level of rock columns passes stress down to the next lower level of columns. Secondary topples are induced at lower

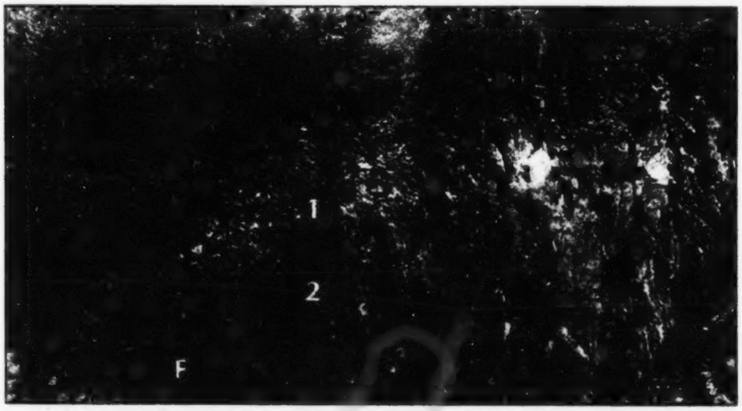


FIGURE 11 *Topples in phyllite or phyllitic rocks. Foliation (F), and two sets of joints*

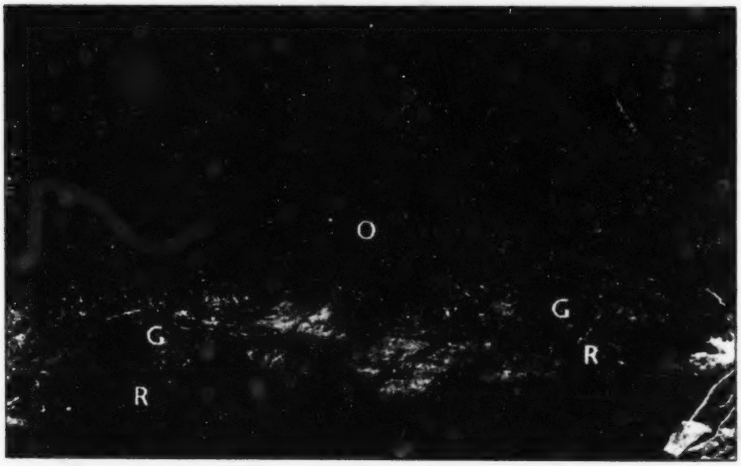


FIGURE 12 *A large toppled slope. Note the vertical foliated bedrock (R) and overturned rock mass (O) above the gently dipping joints (G).*

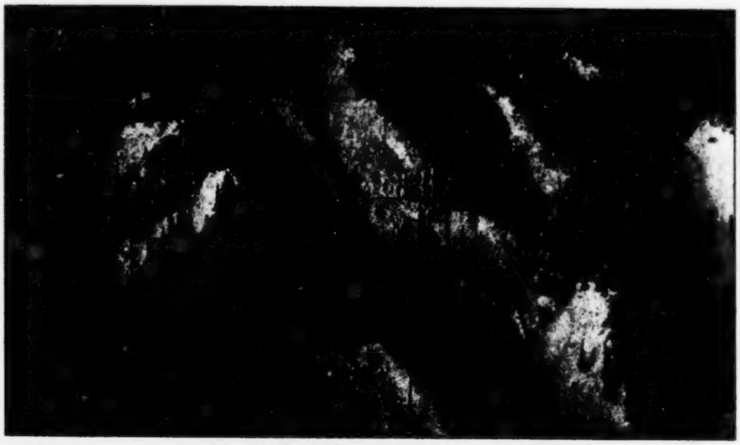


FIGURE 13 *Rock topples, rockslides, and subsequent debris slides and flows have widely developed on phyllite and phyllitic slopes.*

levels by this process. Retrogressive development is caused by the removal of lateral support by either toe erosion or a substantial overturn of the front column(s), leading to the lateral development of topples involving a large volume of material. Good examples were found where the lateral development of topples resulted in a large volume of toppled rock mass resting on the surface of separation. In these examples, the gently dipping shear joints may also become the surfaces of rupture for future debris slides.

Large, deep-seated rockslides are also very common in some metamorphic rocks: phyllite, slate, phyllitic limestone, and serpentinite (Figures 14 and 15). Sometimes, rock spreads also occur in schist and metamorphic limestone (Figure 16).

The following summarizes our findings about terrain stability problems in metamorphic rocks:

- Many terrain stability problems have occurred within certain bedrock types, including sedimentary rocks of Cretaceous and Jurassic ages and metamorphic rocks: phyllite, slate, schist, phyllitic limestone, and serpentinite in the region.
- In flat-lying or gently dipping, interbedded shale, mudstone, and sandstone of Cretaceous age, rockslides, rockfalls, and subsequent debris flows are frequent.
- In closely folded or steeply dipping, interbedded shale, mudstone, and sandstone of Jurassic age, rockfalls, rock topples, and subsequent debris flows are common.
- In metamorphic rocks, especially in phyllite, slate, schist, phyllitic limestone, and serpentinite, rock topples, rockfalls, rockslides, and subsequent debris flows are dominant.

TERRAIN STABILITY PROBLEMS IN CLAYEY MORAINAL DEPOSITS

Morainal deposits cover a large part of the Prince George Forest Region. The morainal deposits in the region can be divided into four subtypes: blocky

FIGURE 14 *A large, deep-seated rockslide in schist in the Pesika Creek valley.*

FIGURE 15 *A very large, deep-seated, rapidly moved rockslide in metamorphic rock occurred on the west side of the Finlay River. Numerous similar rockslides have occurred on the mountain slope, which indicates that the slope has all necessary conditions, especially similar lithology and structures, for rockslides to initiate.*

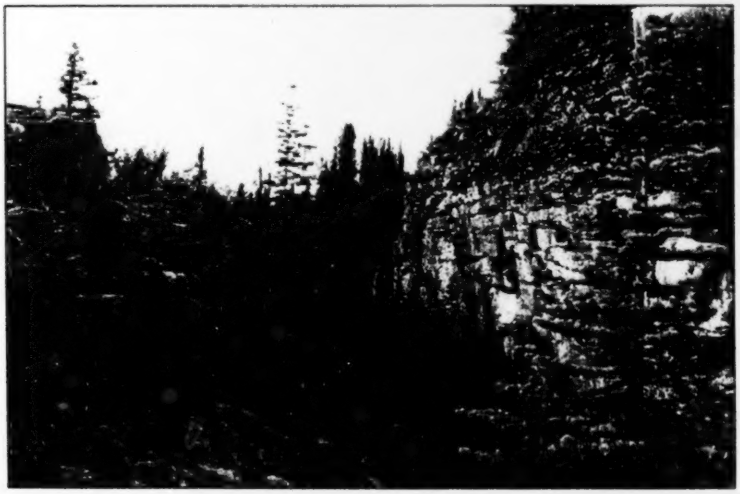


FIGURE 16 *A rock spread in schist in the Pesika Creek area.*

(stony), sandy, silty, and clayey. Terrain stability problems in morainal deposits are common. Most debris slides have occurred in clayey morainal deposits, but very few slides occur in coarse-textured till. Special attention should be paid to clayey till in the region. Very good examples of debris slides developed in clayey till were found in the southwest portion of Dawson Creek Forest District, especially in the Fisher Creek valley and Tumbler Ridge area.

From 1995 to 1996, a main mining road was built in the Fisher Creek valley. After road excavations at the toe of slopes or the mid-slopes, a large number of debris slides occurred. It was very difficult to stop slope movement and maintain the road. Toe support, drainage, and bioengineering work was carried out. The cutslopes are still unstable. Numerous rills and small gullies have developed on the cutslopes, even on moderately sloping grass-seeded slopes. Shallow debris slides have also occurred on these cutslopes as well as on some fillslopes. Further engineering work will be required to stabilize these slopes (Figures 17–19).

Similar debris slides in clayey till were also observed in the neighbouring area to Fisher Creek and in the Tumbler Ridge area, Dawson Creek Forest District (Figures 20 and 21).

All these examples are located in the Rocky Mountain Foothills. It is assumed that the clay and silt particles in tills there were derived from the local bedrock or their weathering products. These Jurassic sedimentary rocks contain substantial layers of shale, especially coal-bearing shale. The clay particles have very low strength, especially when they are fully saturated, and silt particles are very sensitive to surface erosion.

A similar situation is also seen in the Akie River and Pesika Creek valleys, and in the Omineca Mountains where debris slides have occurred in clayey till where the clay fraction is derived from broken or weathered metamorphic rocks: phyllite and serpentinite. Debris slides may also occur in other areas where local bedrock favours the development of clayey till.

The following summarizes our findings about terrain stability problems in clayey morainal deposits:

- Morainal deposits cover most of the Prince George Forest Region. They can be divided into four subtypes: blocky, sandy, silty, and clayey.
- Terrain stability problems occur most frequently in clayey morainal deposits.
- The main types of terrain problems in clayey morainal deposits are debris slides and debris flows.

TERRAIN STABILITY PROBLEMS IN COLLUVIAL DEPOSITS PRODUCED FROM THE BEDROCK TYPES NOTED ABOVE

Many debris slides and debris flows have occurred in the Prince George Forest Region in colluvial deposits produced from the bedrock types noted previously. These terrain stability problems are strongly dependent on the fine particles derived from the weathering products of these rock types. These fine particles, carried downward by groundwater, accumulate at depth and form weak zones that play a very important role in the subsequent stability.

Debris Slides in Colluvial Deposits

In the Akie River and Pesika Creek valleys, many rock topples lead to rapid slope movements, typically debris slides or debris falls. Debris slides within

FIGURE 17 *Unstable cutslope along the mining road in the Fisher Creek drainage. Note that the cutslope is only 3–4 m high with moderate to moderately steep slopes. Despite hydro-seeding, this slope is still unstable.*

FIGURE 18 *The cutslope in till in the Fisher Creek drainage is still unstable after grass seeding.*

FIGURE 19 *Another cutslope on the mining road in the Fisher Creek drainage.*

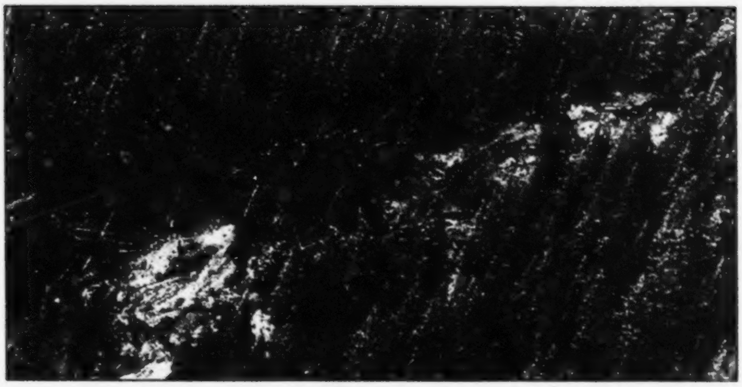


FIGURE 20 *A large, rapidly moved composite debris slide–debris flow in till in the Rocky Mountain Foothills.*

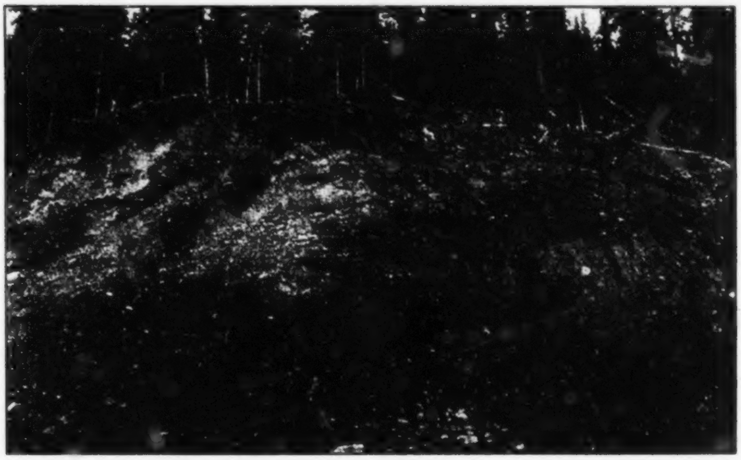


FIGURE 21 *Debris slump/slides developed on a cutslope in till in the Tumbler Ridge area, Dawson Creek Forest District.*

toppled material are widespread in the study area. The fine particles, consisting mainly of silt and clay, are the weathering products of overturned and broken phyllite, phyllitic limestone, slate, and phyllitic slate. These fine particles are transported by groundwater through cracks and fissures. They eventually reach and deposit on gently dipping shear surfaces or joint planes. The gradual accumulation of fine particles results in the formation of a weak layer (or film) on the top of the gently dipping joint surfaces and substantially reduces the shear strength of the displaced mass. This process finally transforms the surface of separation of topples into a potential surface of rupture. When stream erosion removes toe support or further toppling adds an extra driving force to the slope, debris slides take place (Figures 22 and 23).

This mechanism can also be applied to the colluvial deposits derived from interbedded shale, mudstone, and sandstone in the Interior Plains and the Rocky Mountain Foothills, as well as large colluvial/alluvial fans in the Akie River and Pesika Creek valleys. Small to medium-sized debris slides are common on the truncated front part of some fans.

Debris Flows in Colluvial Deposits

Many debris flows have occurred in the toppled material in the Akie River and Pesika Creek valleys. Rock topples and subsequent debris slides supply large quantities of loose debris that rest on slopes or are stored in gullies/creeks. Meltwater and/or heavy rain may work the loose debris into slurry and finally into debris flows. Fine particles in the debris play an important role in the initiation of these debris flows. Different sizes and ages of colluvial/alluvial fans formed by debris flows are very common in the area. These fans contain a substantial portion of fine particles and small pieces of rock fragments. Debris slides and debris flows may occur in areas where toe erosion exposes the weak layers within the fan deposits (Figure 24).

This mechanism can also be applied to the colluvial deposits derived from interbedded shales, mudstones, and sandstones in the Interior Plains and the Rocky Mountain Foothills.

The following summarizes our findings about terrain stability problems in colluvial deposits:

- The accumulation of displaced materials, especially fine particles, plays the most important role in the occurrence of debris slides and debris flows in colluvial deposits.

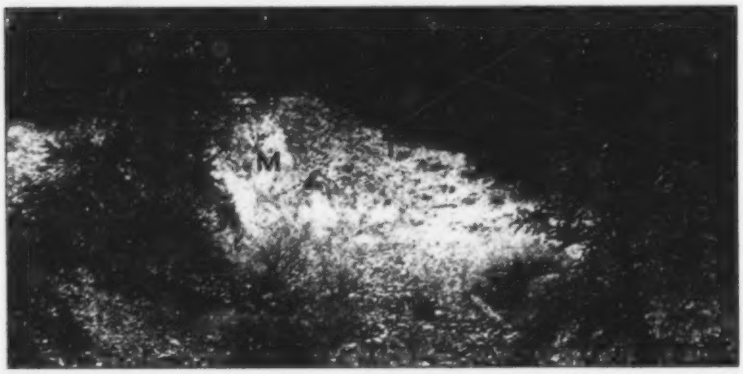


FIGURE 22 *A debris slide occurred in toppled material. Toppling (T) is still going on above the main scarp (M) of the debris slide.*

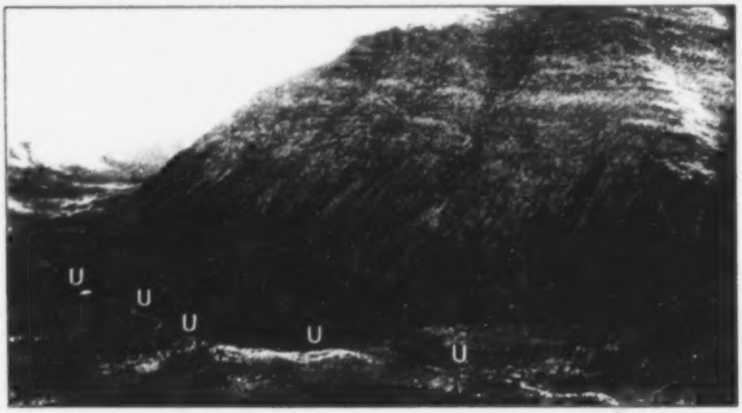


FIGURE 23 *Slope stability problems (U) along the truncated fronts of colluvial fans.*

FIGURE 24 *A typical debris flow and snow avalanche gully in the Akie River valley.*

- The accumulation of toppled materials from particular metamorphic rocks may lead to large debris slides and debris flows. The weathering products and colluvial deposits derived from Cretaceous sedimentary rocks in the Fort St. John Forest District are vulnerable to landslides. Debris slides are common in these materials.

CONCLUSIONS

Different types of terrain stability problems occur in different types of surficial materials. For example, earth slides, earth flows, and serious surface erosion occur in glaciolacustrine and lacustrine deposits; rock topples, rockslides, rockfalls, and consequent debris flows occur in certain lithologies; debris slides and debris flows occur in clayey morainal deposits; and debris slides and debris flows are common in colluvial deposits produced from the rock types noted previously.

Most terrain stability problems in the Prince George Forest Region have occurred in these four types of materials. A sound understanding of geotechnical properties of these materials and a clear picture of the distribution of these materials will improve road engineering and forest management in the region.

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REFERENCES

Cruden, D.M., X.-Q. Hu, and Z.Y. Lu. 1993. Rock topples in the highway cut west of Clairvanx Creek, Jasper, Alberta. Can. Geotech. J. 30:1016–23.

Cruden, D.M., T.R. Keegan, and S. Thomson. 1993. The landslide dam on the Saddle River near Rycroft, Alberta. Can. Geotech. J. 30:1003–15.

Cruden, D.M., Z.Y. Lu, and S. Thomson. 1997. The 1939 Montagneuse River landslide, Alberta. Can. Geotech. J. 34:799–810.

Cruden, D.M. and D.J. Varnes. 1996. Landslide types and processes. *In* Landslides: Investigation and mitigation. A.K. Turner and R.L. Schuster (editors). Transportation Res. Board, Washington, D.C. National Academy Press. Spec. Rep. No. 247, 36–75.

Evans, S.B., X.-Q. Hu, and E.G. Enegren. 1996. The 1973 Attachie slide, Peace River, near Fort St. John, British Columbia, Canada: a landslide, with a high-velocity flowslide component, in Pleistocene sediments. *In* Proc. 7th International Symp. on Landslides, Trondheim, Norway. Balkema, Rotterdam, Netherlands. 2:715–20.

Goodman, R.E. and J.W. Bray. 1976. Toppling of rock slopes. *In* Proc. Rock Engineering for Foundation and Slopes, Aug. 15–18, 1976, Boulder, Colo. Am. Soc. Civil Eng., New York, N.Y. pp. 201–34.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. B.C. Dep. Mines and Petroleum Resour., Victoria, B.C. Bull. 48.

Lu, Z.Y., D.M. Cruden, and S. Thomson. 1998. Landslides and pre-glacial channel in Western Peace River Lowland, Alberta. *In* Proc. 51st Can. Geotechnical Conf., Edmonton, Alta. 1:267–74.

Lu, Z.Y. and M. St. Arnaud. 2002. Landslides in Cretaceous interbedded sandstone, mudstone, and shale in the Fort St. John Forest District, British Columbia. *In* Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proc. P. Jordan and J. Orban (editors). May 23–25, 2001, Nelson, B.C. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

Lu, Z.Y., M. St. Arnaud, and K. Simonar. 1998. Slope stability problems in glaciolacustrine deposits in the Prince George Forest Region, B.C. *In* Proc. 51st Can. Geotechnical Conf., Edmonton, Alta., 2:589–95.

———. 2000. Characteristics of landslides in glaciolacustrine deposits in northern British Columbia, Canada. *In* Proc. 8th International Symp. on Landslides, Cardiff, Wales. Thomas Telford, London, U.K., 2: 1065–71

Lu, Z.Y., K. Simonar, and M. St. Arnaud. 1998. A chain of slope movements in phyllites and phyllitic limestones in the Akie River valley, Mackenzie, B.C. *In* Proc. 51st Can. Geotechnical Conf., Edmonton, Alta., 2:565–72.

Ryder, J.M. 1978. Geology, landforms and surficial materials. *In* The landscapes of British Columbia. K.W.G. Valentine, P.N. Sprout, T.E. Baker, and L.M. Lavkulich (editors). B.C. Min. Environ., Resour. Analysis Br., Victoria, B.C., pp. 11–33.

Schaefer, D.G. 1978. Climate in the soil landscapes of British Columbia. *In* The landscapes of British Columbia. K.W.G. Valentine, P.N. Sprout, T.E. Baker, and L.M. Lavkulich (editors). B.C. Min. Environ., Resour. Analysis Br., Victoria, B.C., pp. 3–10.

Landslide Risk Analysis of Historic Forest Development in the Interior of British Columbia—Challenges Encountered at Fall Creek

FREEMAN R. SMITH AND CALVIN D. VANBUSKIRK

ABSTRACT

In June 1990, the Fall Creek area east of Enderby, B.C., experienced about 66 landslides. These landslides impacted forested slopes and forestry roads, destroyed several BC Hydro transmission towers, damaged and destroyed houses, and cut off highway access to the area, resulting in the evacuation of residents. These slides also destroyed a fish farm, several licensed water intakes, and impacted on the Shuswap River (salmon spawning habitat). The total cost of the slide events is estimated to exceed $3 million. The 66 landslides occurred during a 3-day period within 12 small watersheds encompassing 3000 ha. The area has experienced logging activity since the 1940s and contains well over 100 km of active and overgrown roads and trails, many of which are no longer visible on recent aerial photographs. The task of sorting out the contribution of the historic logging activities to the landslide events was described by others as "formidable at best." The challenges in commencing such a project included (1) determination of the potential costs of the assessment work; (2) estimating if any practicable conclusions could result from such a study, given the vast network of roads and overgrown trails; and (3) conducting the fieldwork during the narrow work window of the spring freshet (the importance of which became very clear shortly after peak runoff as large streams began to disappear). The fieldwork used an observational approach, which required continuous modification as the work progressed. The fieldwork began with mapping the natural and road drainages along road corridors. The field information was plotted daily on a 1:10 000 scale base map. The plotted information revealed inconsistencies in stream volume and the location of flows. The drainages between road corridors were then traversed. The "piecing together" of the complex series of drainage diversions eventually resulted in the creation of a site drainage map, which showed the interaction between natural drainage and road/trail structures. By overlaying this map with the landslide locations, a link between many of the 66 landslides and drainage diversions was revealed. It is judged that drainage diversions were a significant contributing factor in most of the landslides that occurred in 1990. The creation of this site drainage map proved to be a valuable tool in evaluating the landslide activity associated with historic logging practices. The field studies also conclude that the Forest Practices Code and current forest practices would likely have prevented many of these slides.

INTRODUCTION

Most landslides in the southern Interior of British Columbia can be attributed to drainage diversions and concentration of surface and near-surface water flows. This paper summarizes some of the challenges encountered in assessing the landslide risks posed by historic logging activity in one area. This discussion also provides a reminder of the devastating effects that landslides can have in the Interior.

The study area contains several hundred kilometres of active and overgrown roads and trails, many of which are no longer visible on recent aerial photographs. Conducting a risk analysis within an area with so many roads and trails produced several challenges.

SITE HISTORY

The Fall Creek study area is a large face unit on the north side of the Shuswap River, located approximately 15 km east of Enderby, B.C. The area consists of about 25 small drainage basins, most of which are in the order of 100 ha. The area has been subjected to logging activities since the 1940s. In the early 1980s, the steeper forested slopes in the area of the 1990 landslides and the plateau area upslope of the 1990 landslides were subject to clearcut harvesting.

From June 11 to 13, 1990, a major spring rainstorm triggered 66 landslides in the Fall Creek area. These events occurred near the end of a long period of above-average precipitation. Most of the precipitation fell as rain, with rain on snow occurring above approximately 1300 m elevation. The landslides damaged or destroyed:

- homes and private property (vehicles and equipment)
- several BC Hydro transmission structures
- telephone lines
- water intake structures
- forested slopes
- access roads

Channel avulsion resulted in some landslides and subsequent flooding, which impacted a local fish farm and other small businesses, and delivered sediment into the Shuswap River (important fish habitat). The landslide and flooding events cut off highway access to the area. Many people left the area on foot and some were evacuated by helicopter.

On June 11, landslides destroyed three hydroelectric transmission towers, cutting off the power supply from the Revelstoke Dam. Both of the 500 kV transmission lines were down for 3 days and one line was down for 2 weeks. The loss of revenue to BC Hydro was estimated to be in the millions of dollars per hour. The total cost of the landslide damage in the Fall Creek area not including the BC Hydro revenue loss is estimated to be over $8 million.

On June 12, the same storm event had devastating effects east of Kelowna at Philpott Road, which included loss of life (Cass et al. 1992).

Following the Fall Creek landslide events, the Provincial Emergency Program (PEP) retained a geotechnical engineering consultant to assess the area.

The consultant concluded that the preferred way to protect residents at the bottom of the slopes would be to relocate some homes and construct deflection and training berms to divert future landslides. They also recommended that road structures and drainage issues related to past upslope development be assessed in the field (Thurber 1990a, 1990b).

In 1998, Riverside Forest Products and the B.C. Ministry of Forests approached Terratech Consulting Ltd. to conduct a joint terrain stability mapping and landslide risk analysis study of about 35 000 ha in the Hunters Range area, which included the Fall Creek area. The task was to identify and, if possible, develop remedial measures to reduce the landslide risks from historic logging activities (non-status roads) that are not covered by the current Forest Practices Code. The risk analysis of Hunters Range quickly focused most of its efforts in the Fall Creek area.

CHALLENGES ENCOUNTERED

The three main challenges encountered included (1) creating a realistic budget, (2) creating a base map, and (3) scheduling (timing) of the fieldwork.

Budgeting

At the outset, project budgets were requested for all of the stages, from the beginning office stage to the final prescription stage. During the office portion of the risk analysis,[1] the large number and extent of old roads and trails were noted and the task of assessing the influence of the past development on terrain stability appeared to be daunting. Air photos and 1:20 000 scale topographic maps provided little information regarding the present drainage conditions and could not be relied upon to prepare a budget. Drainage diversions, plugged ditches, cross-ditches, and water concentrations typically cannot be seen on air photos. With hundreds of kilometres of roads and trails, pullback and/or re-contouring all of the roads and trails was considered counter-productive (potentially creating more problems) and very expensive. It was considered unlikely that all the old roads and trails would be deactivated. Accordingly, no practical method to prepare cost estimates for assessing this face unit (multiple drainage basins) with the complex road networks was considered feasible. Cost estimates for these assessments on a per-hectare or per-kilometre basis were considered to be unrealistic. (Perhaps when dealing with a single, linear feature upslope of an identified resource, such as a mainline road upslope of a fish-bearing river, a cost per kilometre estimate could be provided.) Preliminary fieldwork was completed before preparation of a budget for field assessment.

Completion of terrain hazard and risk analysis projects in complex "face unit" areas should include budgets for a pre-field office phase, a preliminary fieldwork phase, a final fieldwork phase, and a reporting and prescription phase. The budget for subsequent phases may not be realistically estimated without the benefits of the results of the previous phase.

Base Maps

The identification of both existing and potential drainage diversion sites associated with past road and trail construction is a ground-intensive procedure. This work is often made more difficult (and time consuming) because of the lack of high-quality topographic or planimetric maps showing the location of the old roads and trails and the revegetation of the trails and roads. The detail and reliability of the topographic and planimetric information on the readily available TRIM (Terrain Resource Inventory Mapping) maps is significantly less than that required to assess the impacts and potential impacts of past forest development activity on site drainage and slope stability conditions. The use of historic aerial photographs is essential for the identification of past or recent landslide activity downslope of road and trail sites. As new roads are constructed within a given area, the pattern of the older roads and trails becomes obscured. As a result, the analysis requires the use of multiple years of historic air photos. Given that the scale of most air photos is between about 1:15 000 and 1:30 000, trails associated with ground-based and selective timber harvesting become difficult to delineate. In many areas within the Fall Creek study, trails were noted to be spaced as close as 20 m apart. These issues make the analysis of the spatial relationship between the road and trail drainage issues and landslide or potential landslide sites difficult to resolve and time consuming. These problems are compounded in areas of multiple landslide events and extensive historic development activity, as in the Fall Creek area.

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[1] Risk Analysis: for definition see CSA (1997).

To address some of the challenges of assessing the existing road and trail drainage issues in the Fall Creek area, a detailed topographic map of the area was prepared. This map was prepared from both 1990 and 1994 aerial photography, with additional planimetric information on road and trail locations being obtained from older photography (dating to about 1970). This map was prepared at a scale of 1:5000 and has a contour interval of 5 m. By plotting the field information regarding road and trail drainage issues on this map, a high degree of correlation was noted between the landslide locations and the presence of upslope drainage diversions. In addition, some additional target sites (sites of potential drainage concerns that could impact on the downslope resources) were identified after the final map was prepared.

It is suggested that when performing risk analyses for face units, high-quality topographic base maps with detailed planimetric information be prepared.

Scheduling of Fieldwork

During the preliminary fieldwork (spring of 2000), site drainage information was collected along the drivable roads. This information was compiled onto a base map to form a "site drainage map" at a 1:5000 scale. As a result of this work, it was concluded that existing and potential drainage diversions posed a clear landslide risk to the downslope values considered in the study. Following the creation of a site drainage map, foot traverses of the streams and diverted drainages between the drivable roads were undertaken to tie together the drainage details. During the fall, it became apparent that fieldwork outside of the effective (freshet) work window was not reliable. Ditch and stream flows were not readily visible. Water flows noted in swales and flowing down roads earlier during the freshet had dried up. The connections between altered drainage and past instability that was obvious during the freshet became obscure in the fall. It was unclear in the fall whether a visible diversion scour path was active or an old feature that subsequent road works had corrected. The window of time for effective observation was over. In the Interior, the fall runoff conditions are generally not similar to the spring runoff conditions. Given the difficulty and uncertainty with assessing surface water flows in the late summer and early fall, some of the final fieldwork was delayed until the spring of 2001.

It is suggested the fieldwork for conducting risk analyses not be undertaken outside of the spring freshet season in the Interior.

RESULTS

A total of 66 landslides were noted to have occurred during a 3-day period. Landslides in 10 of the 25 watersheds impacted resources or values in the valley bottom. By superimposing the site drainage information onto the landslide location information, it became apparent that a significant number of the landslide sites appeared to be linked to drainage diversions. Some diversions were judged to be linked to three or more landslides as the diverted flows cascaded down the slope across roads and trails. For example, it is possible that the loss of drainage control in the upper reaches of Newman Creek contributed to between 10 and 15 of the reported 66 landslides that occurred in June 1990. These particular landslides contributed to debris flow activity within existing drainages, which impacted several houses, private property, the Mabel Lake Road, and Shuswap River. Had properly placed culverts, cross-ditches, and swales been incorporated into the road network, a significant number of observed diversions may have been prevented. Note that most of the landslides, which initiated at higher elevations (> 1100 m), appeared to be natural events (i.e., they were not linked to development activity). Some of the landslides on the steeper slopes in the developed areas also appear to have been natural events.

DISCUSSION

The risk analysis work carried out within the Hunters Range (Fall Creek area) identified a number of sites and areas that pose a significant risk to one or more of the resources considered within this study. The risks posed by most of these sites are related to the existence of, or potential for, surface water or near-surface water flow concentration and diversion onto unconditioned, moderately steep to steeply sloping terrain. The field review of a number of the existing landslides located within, and downslope of, past areas of forest development (typically where roads and trails change natural drainage patterns) suggests that ≥ 60% of the landslides can be attributed to one or more of the following site conditions:

- a lack of a coordinated drainage system;
- poorly installed drainage structures;
- improperly located drainage structures; or
- poorly maintained drainage structures.

As many of the landslides noted in the field could be readily linked to drainage problems, the risk analysis focused on the identification of existing and potential drainage diversions or concentrations. These situations are judged to represent a short-term[2] risk, where landslide activity could be initiated as a result of the next spring freshet or significant rainfall event. It was concluded that repairs to drainage problems would significantly reduce the likelihood of landslide activity and should be undertaken prior to considering long-term[2] issues such as perched fills (oversteepened road fill reinforced by organic debris).

In recent years, wood-supported fills have been pulled back and in many cases the materials have been end-hauled to dump sites. This approach to landslide hazard mitigation and risk management is expensive. Significant funds are required for the pullback of wood-supported fills to reduce the landslide hazards and risks within a given area. A more cost-effective risk-mitigation strategy would be to address drainage problems. In many cases, landslide hazard mitigation projects requiring drainage works often include extensive fill pullback programs. This significantly increases the cost estimates of most projects, resulting in the deferral of both the drainage and fill pullback work. This leaves the "short-term" hazards (and risks) related to drainage not mitigated.

SUMMARY

The risk analysis work conducted within the Fall Creek study area has illustrated the importance of establishing and maintaining good drainage control on all roads and trails. The loss of control on a single stream channel can lead to extensive landslide activity and damage to forest land and other downslope resources. Depending on the location of the diversion and the extent and condition of the roads and trails downslope of the diversion site, a single diversion can result in multiple landslide events.

Based on the results of the Fall Creek risk analysis work, it is suggested that the following procedure be considered for landslide risk analysis projects in areas of past forest development in the Interior:

1. Identify the areas where high-value resources are located. This may be considered to be the point or area of interest (AI).
2. Identify areas or zones upslope of the AI that include slope stability class III, IV, or V terrain and that have been subjected to past forest development activity or have had forest development upslope. This will require the use of existing maps and both recent and historic aerial photographs.
3. Collect or prepare high-quality maps of the area that show the existing road and trail locations and existing stream channels.
4. Conduct field mapping of the site drainage conditions during the spring freshet and collect detailed information on the existing road/trail drainage network. This should include, but not necessarily be limited to:
   - road grade (adverse vs. favourable), swale locations, drainage divide locations, and cross-ditch and water bar (and reverse water bar) locations;
   - culvert locations and conditions, and ditch locations and conditions;
   - direction of ditch line flow, seepage locations, stream channel locations, and location of ponded water;
   - evidence of water diversion, stream erosion or deposition, and scour on road surface, cutslope, or fillslope;

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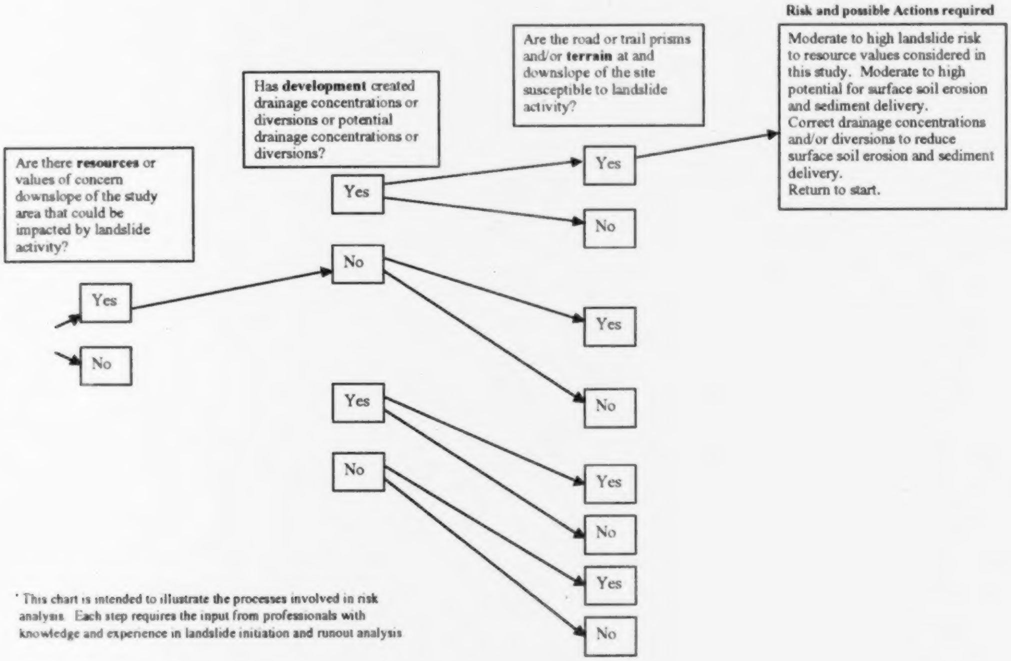
[2] Short-term risk is used to describe a higher level of risk associated with a short return period event. Long-term risk is used to describe a lower level of risk, associated with a long return period event. See RIC (1996).

- landslide activity from cutslope or fillslope, excessive flows down ditch line, and excessive (particularly unconfined) flows over the cutslope and fillslope;
- evidence of recent repairs to culvert or other structures, and additional or replaced culverts; and
- dry channel locations with evidence of past flow, and natural swale or gully location (that presently may not have flows).

5. Compile this site drainage information onto the base map and determine if other areas (perhaps with more difficult access) should be assessed in the field.
6. Traverse all stream channel reaches (including non-classified drainages) that extend through the areas of past development.
7. Assess in the field the potential for drainage diversions to occur and the likelihood that landslides will be triggered.

CONCLUSION

Drainage concentrations and diversions are responsible for most of the development-related landslides in the southern Interior. Understanding the interaction between natural and development-related drainage is critical in analyzing landslides within and downslope of development. Figure 1 illustrates the relationship between resource values, development, and terrain, and how these components should be addressed in landslide risk analyses.


Are there **resources** or values of concern downslope of the study area that could be impacted by landslide activity?
Yes
No
Has **development** created drainage concentrations or diversions or potential drainage concentrations or diversions?
Yes
No
Yes
No
Are the road or trail prisms and/or **terrain** at and downslope of the site susceptible to landslide activity?
Yes
No
Yes
No
Yes
No
Yes
No
Risk and possible Actions required
Moderate to high landslide risk to resource values considered in this study. Moderate to high potential for surface soil erosion and sediment delivery.
Correct drainage concentrations and/or diversions to reduce surface soil erosion and sediment delivery.
Return to start.

' This chart is intended to illustrate the processes involved in risk analysis. Each step requires the input from professionals with knowledge and experience in landslide initiation and runout analysis

FIGURE 1 *Method of analyzing landslide risk in areas of historic forest development.*

Canadian Standards Association (CSA). 1997. Risk management: guidelines for decision-makers, CAN/CSA-Q850-97, 1997. Etobicoke, Ont.

Cass, D.E., B. Kenning, and G. Rawlings. 1992. The Philpott Road debris failures – Kelowna, B.C., 1990: The impacts of geology, hydrology and logging activities. *In* Geotechnique and Natural Hazards. Symp. sponsored by Vancouver Society and Canadian Geotechnical Society, May 6–9, 1992. BiTech Publishers Ltd., Vancouver, B.C., pp. 319–29.

Resource Inventory Committee (RIC). 1996. Terrain stability mapping in British Columbia—A review of suggested methods for landslide hazard and risk mapping. Victoria, B.C.

Thurber Engineering Ltd. 1990a. Debris flow hazard assessment Fall Creek Slide Area. Report to the Provincial Emergency Program, B.C. Min. Solicitor General, Victoria, B.C.

———. 1990b. Fall Creek Slide Area recommended mitigation measures. Report to the Provincial Emergency Program, B.C. Min. Solicitor General, Victoria, B.C.

Terrain Stability Field Assessments in "Gentle-over-Steep" Terrain of the Southern Interior of British Columbia

BILL GRAINGER

ABSTRACT

In the southern Interior of British Columbia, most significant landslides associated with forestry operations are related to drainage diversions by forest roads and trails located on gentle to moderately sloping terrain, some distance upslope from steeper, more landslide-prone terrain. The underlying slope stability processes and the concepts of drainage interception, concentration, and redirection are discussed. Five areas of focus are suggested for doing terrain stability field assessments in this environment: (1) the sensitivity of downslope terrain: how much additional water can the slope handle before failing? (2) site moisture regime: how much slope water could be available to be intercepted? (3) site geotechnical conditions: how effectively will the road prism intercept water? (4) road grade configuration: how effectively will the road alignment concentrate and redirect water? and (5) drainage connectivity between the road prism and downslope terrain: how will redirected water behave between the road prism and potentially unstable downslope terrain? Some methods and tools for answering these questions, and some design suggestions to deal with sensitive areas are presented.

INTRODUCTION

This paper discusses the terrain, hydrologic, and forest development factors that should be investigated as part of any terrain stability field assessment where there is the potential for the particular class of slope failures associated with forest industry practices known as "gentle-over-steep" (GoS) landslides. In the southern Interior of British Columbia in the last several years there has been an increasing awareness that most significant landslides related to forest industry practices in this region have been GoS-type landslides. GoS landslides in the Shuswap and Okanagan Highlands have been responsible for the evacuation of residents, property damage, and litigation (Anderson et al. 1997; Dobson Engineering Ltd. 1997), and loss of life (Schwab et al. 1990).

Until recently there has been little discussion of the occurrence, processes, and management implications of this class of landslides in the forestry geotechnical literature, or explicit recognition in forest practices regulations in British Columbia of the need to manage the risks associated with these slides.

Gentle-over-steep landslides are described as occurring "some distance below roads, below a culvert or a point of accidental drainage discharge [where] the road itself is on gently-sloping, low-hazard terrain, and the landslide occurs on steeper terrain below" (Jordan 2001). Landslides generally occur near a slope gradient break between the flatter lying terrain on which the road is constructed, and steeper-gradient terrain downslope. This may occur from several metres to several hundred metres downslope of the road, and the physical connection between the forestry development and off-site landslide consists entirely of water movement between the two.

The southern Interior of British Columbia is defined in this paper as the area covered by the Kamloops and Nelson Forest Regions. This paper builds on earlier work in the Nelson Forest Region (Jordan 2001), which provided both landslide inventory data for the Slocan Valley in the southern Columbia Mountains, and discussed GoS landslide characteristics and processes. The Slocan study inventoried approximately 190 strictly drainage-related failures, many of which were GoS landslides. Most of the conclusions are drawn from observations of about 100 GoS landslides in the Shuswap Highlands and, to a lesser degree, on the Kamloops Plateau, both in the Kamloops Forest Region.

This paper first discusses GoS landslide characteristics and processes, to provide the background for understanding the suggested hazard assessment procedures. GoS landslide risks in the southern Interior and the current regulatory environment in British Columbia at the time of this writing are briefly discussed. The suggested procedure for conducting an assessment of GoS landslide hazard is broken down into five terrain and development factors, and each is discussed with examples. Finally, a framework for managing GoS landslide hazards is briefly presented.

GOS LANDSLIDE CHARACTERISTICS AND PROCESSES

Forest roads, and to a lesser extent trails, situated on gentle (6–26%) to moderately sloping (27–50%) terrain can intercept surface and subsurface hillslope drainage. Drainage accumulates or is concentrated down the ditch or road surface, and is redirected to a single exit point from the road. This is usually a culvert, cross-ditch, or switchback, but can be a random point of discharge caused by road prism failure. This discharge then travels as either surface or subsurface flow, some distance across gentle to moderate-gradient terrain downslope of the road. When it reaches a slope break to moderately steep (50–70%) to steep (> 70%) gradient slopes, a landslide can occur.

Although deep-seated landslides have been observed downslope of the outlet of concentrated road drainage, most GoS landslides occur in shallow, relatively permeable weathered till or colluvium overlying relatively impermeable till or bedrock.

Because they are much longer than deep, these landslides can be modelled by an infinite slope analysis, with the soil shear strength, S_s, or the resistance to sliding, expressed as:

$$S_s = c' + (\sigma - \mu) \tan\phi' \qquad (1)$$

where: c' = apparent cohesion, σ = the total normal stress due to the weight of soil and water, μ = pore pressure due to the depth of the saturated zone, and ϕ' = the effective angle of internal friction of the soil. A slope failure will occur when the shear stress or the forces promoting sliding (the weight of soil and water on the slope) exceed the shear strength.

The thin weathered till and colluvial soils on steep slopes in southwestern British Columbia frequently have a very low clay content and are often considered cohesionless. It is assumed that on marginally stable slopes, the effect of differing internal friction angles of the commonly encountered morainal and colluvial soils of the southern Interior is minor compared with the effect of changes in pore pressures. Because the landslide-prone terrain is some distance downslope of the road prism, and is as likely to occur in forested as in harvested terrain (Jordan 2001), these landslides are presumably caused by the artificially increased water volume from the road. This extra water increases pore water pressure (μ) and decreases the effective stress ($\sigma - \mu$) in soils on the steeper gradient slopes some distance downslope of the road.

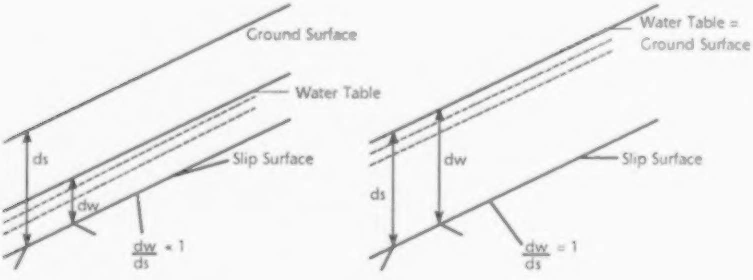
It has been shown that for cohesionless soils, as the ratio of the height of the saturated zone (*dw*) to the total soil column depth (*ds*) increases, the effective stress decreases (Skempton and DeLory 1957). In this paper the ratio *dw*/*ds* is used as an expression of the effect of the saturated zone on slope stability. Note that because effective stress, and thus shear stress, is proportional to the ratio *dw*/*ds*, and not simply the saturated zone height (*dw*), shallow cohesionless soils are less stable than deep soils, given the same saturated zone depth.

Figure 1 shows long-term maximum water table levels for steeper slopes on the Coast and in the southern Interior of British Columbia, as implied by inventories of forest development related landslides (Table 1).

TABLE 1 *Comparative landslide statistics*

	Landslide cause (%)				
Region	Clearcut (root strength)	Drainage (off-site)	Road fill	Cutslope/ Others	*dw*/*ds*
Coast Clayoquot Sound, West Coast Vancouver Island (Jakob 2000)	54	0	31	15	=1
Southern Interior Slocan Valley, Columbia Mountains (Jordan 2001)	3	43	47	7	<<1

Note: the symbol << is used to indicate "much less than."



a. Southern Interior

b. Coast

FIGURE 1 *Long-term maximum water table levels for a) Southern Interior, b) Coast.*

Roughly half of all forestry-related landslides on both the Coast and in the Columbia Mountain studies are caused by road prism failures. Of the remaining half, the distribution of landslide causes between the Coast and southern Interior are the opposite of each other. On the Coast, about half of all slides were judged to have occurred in clearcuts with no influence from road prisms or road drainage diversion (i.e., there were no strictly drainage-related or GoS landslides). In the Columbia Mountains, almost half of all slides were off-site, drainage diversion failures, many of which were GoS landslides; clearcut failures were rare. In the Shuswap Highlands, which are characterized by large areas of gently sloping upland plateau incised by lake and river valleys (Figure 2), there is a wider distribution of a gentle-over-steep terrain configuration than in more mountainous areas of the southern Interior. Gentle-over-steep landslides are therefore likely to make up a larger proportion of forestry-related landslides in the Shuswap Highlands than in the Columbia Mountains. The Cariboo Highlands to the north and the Okanagan Highlands to the south are similar in physiography to the Shuswaps and likely in landslide occurrence as well.

While there may be differences between the Coast and southern Interior in terms of slope physiography and soil texture, no parameter is as clearly divergent as the precipitation inputs to each area. Total annual precipitation at valley bottom on the west coast of Vancouver Island is over 3000 mm/yr (Environment Canada 1993). At valley bottom in the south Columbia Mountains it is around 700 mm/yr, and in the Shuswap Highlands it is about 500 mm/yr. Total annual precipitation on the Coast is therefore approximately 4–6 times greater than in the southern Interior. Maximum rainfall amounts in individual rainstorm events are also greater by a similar proportion.

The difference in landslide causes between the Coast and south Columbia Mountains inventories can be explained if we assume that this large difference in precipitation results in different maximum long-term values for the relative depth of the saturated zone in shallow soils (Figures 1a and 1b).

On the Coast, if the water table has periodically been at the highest level possible, at the ground surface, the soil column is totally saturated and further water input runs off as surface flow (Figure 1b). Assuming the soil internal friction angle (ϕ) is relatively unchanging over periods of hundreds to

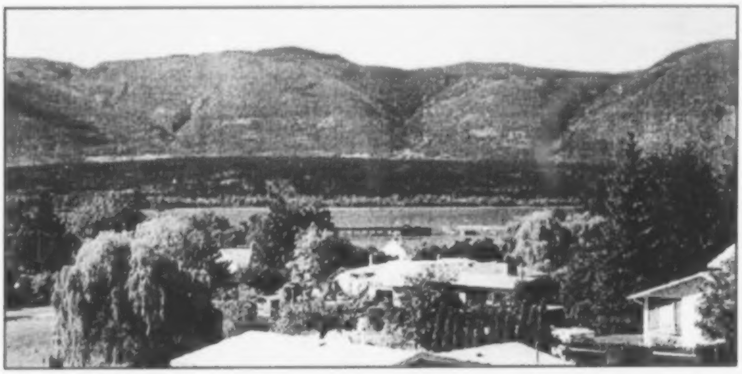


FIGURE 2 *Typical Shuswap Highlands landform at Fly Hills, overlooking the town of Salmon Arm, B.C. Note the gently sloping upland with steeper stream incision into valley walls.*

thousands of years that we are discussing here, for cohesionless soils with the effective stress periodically at the minimal possible value, on some marginally stable slopes it must be tree root strength that is preventing sliding. For many locations on the B.C. Coast, the shear strength equation can be expressed as:

$$S_s = r' + (\sigma - \mu) \tan\phi' \qquad (2)$$

where: r' = root strength. We know this because the coastal inventory results tell us that when we cut trees down and tree roots die and lose their strength, landslides occur.

In the south Columbia Mountains, the inventory shows that there are almost no landslides due to harvesting alone. The much lower precipitation here is generally not enough to effect a high degree of saturation of the soil column on moderately steep to steep slopes (i.e., dw/ds is always <<1, and effective stress remains high) (Figure 1a). Therefore, relative to the effective stress, root strength is a minor contributor to slope stability. In the drier areas of the southern Interior, this effect is probably equally or more pronounced.

Commonly in the southern Interior, therefore, we can have a situation on an otherwise marginally stable slope where, over the long term, there is a large unsaturated portion of the soil column above the saturated zone. If by our forest practices we deliver a volume of water to that slope that is much greater than natural maximums, we can cause unprecedented saturation of this upper soil column and trigger a slide. The landslide inventory results show this—in the southern Interior, when drainage is concentrated by forest roads and redirected onto steeper downslope areas, there are GoS landslides.

A further important effect of road drainage diversion is that the increased flows can be maintained on the marginally stable slope for some time before a landslide occurs. Soil pore pressures can increase and soil shear strength decrease for a long distance downslope. Because the factor of safety is thus lowered over a long downslope distance, when critical factors of safety values are reached at the head of the slope, the whole slope fails and a very large landslide occurs (Jordan 2001). For this reason, GoS landslides are commonly larger than road prism failures, and most large landslides with significant downslope impacts in the southern Interior are GoS slides.

GOS LANDSLIDE RISKS AND REGULATORY ENVIRONMENT

In much of the southern Interior, and particularly in the Shuswap Highlands where uplands are not steep, most steeper slopes are located on river and lake valley walls, and are often directly connected by steep slopes to these watercourses. There is also increasingly widespread human settlement of these lower valley walls, and on valley-bottom fans and floodplains. Thus, landslides on these valley walls frequently impact watercourses that are drinking water sources, as well as on human habitation and private property that are often located in landslide runout zones. While there are about one-tenth the number of landslides per unit area in the southern Interior as on the outer Coast (Jordan 2001), of all forestry-related landslides in British Columbia, GoS landslides in the southern Interior form a significant portion of those responsible for private property damage, litigation against the forest industry, threats to human safety, and loss of life.

In British Columbia at this time, landslide hazards related to forest roads are managed under the Forest Road Regulations (FRR) of the Forest Practices Code (FPC), which requires that before road construction or modification or deactivation, a terrain stability field assessment (TSFA) must be carried out by a qualified registered professional if the area has been recognized as having a potential landslide hazard (FRR Section 4 (5); B.C. Ministry of Forests 2000).

The purpose of a TSFA is "to describe the terrain conditions within a proposed cutblock or *along a proposed section of road* [author's emphasis], evaluate the likely effect of timber harvesting or road construction on terrain stability, and recommend site-specific actions to reduce the likelihood of post-harvesting or road-related landslides..." (B.C. Ministry of Forests 1999). The forest industry has generally interpreted that the need for professional involvement in hazard assessment and road design is triggered by the hazard along the road location, and not the hazard downslope of the road. In the Columbia Mountains, GoS landslides are the primary cause of landslides from newly constructed roads (Jordan 2001). This finding suggests that industry practices are not adequately managing for this type of landslide hazard.

There is provision under the FPC for a B.C. Ministry of Forests District Manager (DM) to direct that a TSFA be carried out in any area where the DM identifies it is required (FRR Section 4 (5) (e); B.C. Ministry of Forests 2000). In at least one forest district, the GoS landslide problem has been recognized, and the DM has issued a directive informing licensees that TSFAs must address areas downslope of proposed roads and cutblocks (D. Hudson, B.C. Min. For. Salmon Arm Forest District, pers. comm., 2001).

In my experience in the Shuswap Highlands, the majority of landslides associated with road modification (upgrades) and deactivation are also GoS slides. Some of the most serious recent landslides in the southern Interior have occurred within a few years of road upgrading (Dobson Engineering Ltd. 1997) or road deactivation (Schwab et al. 1990), and have involved property damage, litigation, and loss of life. Upgrades and deactivation can disrupt long-established drainage patterns that have come to some stable equilibrium with surrounding terrain. Even restoring drainage to what were apparently pre-construction natural drainage paths has caused significant GoS landslides. In potential GoS landslide terrain, an investigation of upslope drainage contributing area and downslope stability conditions is at least as important when planning modification or deactivation of existing roads, as it is when planning new road construction.

Whatever the future regulatory framework for forest practices in British Columbia, regulators and professional practitioners—foresters, geoscientists, and engineers—should ensure that industry practices recognize the potential, and manage, for landslides occurring off-site from developments. The costs to the forest industry of not addressing this issue could turn out to be much greater than that required to manage it properly.

On the positive side, while the off-site GoS landslide potential may require as much or more assessment than the strictly on-site landslide potential, the assessment phase is generally a small part of total development costs. Construction costs are much greater, and it is almost always less expensive to design or correct road drainage than to address road prism stability issues with costly techniques such as full bench and end haul construction, or heavy fill pullback. In the southern Interior, improved assessments of drainage-related off-site landslide hazards should achieve both better management of actual risks, and likely some reduction in total engineering costs.

There are existing guidelines on how to carry out a TSFA and what is considered good professional practice (Horel et al. 1996; B.C. Ministry of Forests 1999; Turner et al. 2001). This discussion is restricted to five specific factors that need to be addressed where there may be a GoS landslide potential. They are:

1. The downslope factor of safety: How much additional water could a steeper slope, located some distance downslope of the road, receive before failing?
2. Site moisture regime: How much surface and subsurface hillslope water runoff could be available to be intercepted?
3. Prism conditions: How could the road prism intercept hillslope runoff?
4. Grade configuration: How could the road alignment concentrate and redirect water?
5. Slope drainage connectivity: How will water move between its exit point from the prism and potentially unstable downslope terrain?

Note that points 1, 2, and 5 address site terrain and hydrologic conditions and points 3 and 4 address road design and construction factors.

There is no set sequence to follow in assessing these factors, but instead an iterative approach needs to be taken. The more hazardous any particular factor or set of factors appears to be, the more detailed the investigation of the others should be. It will become apparent that most of the assessment time should be spent both upslope and downslope from the road location.

The Downslope Factor of Safety

To understand how proposed forestry development may impact downslope stability, it is necessary to have some knowledge of prior slope stability conditions. For GoS landslides, the basic question is how much additional water can the slope receive before a landslide occurs. In geotechnical terms, the factor of safety is the ratio of the resistance to sliding (shear strength, Equation 2) to the forces promoting sliding (shear stress) at the point of potential failure. When the factor of safety drops below 1, failure can occur.

In the forestry context, the assessment of existing slope stability is rarely a quantitative factor of safety analysis using subsurface geotechnical data. Rather, the method is qualitative and comparative. A comparative method requires investigation of existing local landslides, geomorphic and hydrologic processes, and the hillslope response to previous forestry developments in similar terrain in surrounding areas. The investigation of adjacent areas must be thorough enough so that the basis of comparison can be clearly understood. As with all professional geotechnical reports, "Sufficient information and explanation should be provided to allow another qualified professional to follow the author's logic..." (Horel et al. 1996).

Where GoS landslides have occurred in the Shuswap Highlands, as often as not, there is no recent or relic landslide activity visible in the immediate area on pre-failure air photos. This means that the lack of slope instability indicators may *not* be an indication of how sensitive the site could be to drainage diversion, and an understanding of processes in surrounding areas is necessary.

Using air photos and terrain mapping, as well as topographic and bedrock geological mapping prior to fieldwork, will greatly increase the efficient use of field time. If there are existing landslides in adjacent areas, historic air photo series are probably the only way of determining their chronological relationship to forestry developments. Determining the actual cause of existing landslides is critical to making a comparative assessment of areas with similar terrain and proposed development. In areas with a low landslide frequency, it may be necessary to inspect terrain mapping and multiple air photos in a wide area around the assessment site, to determine if there is similar terrain that has or has not been impacted by previous forest development. All relevant landslides should be investigated on the ground to develop terrain stability criteria; this can require as much time as is spent assessing the proposed development and downslope areas.

Jordan found that in the southern Columbia Mountains, GoS landslides typically occur where gentle slopes break to gradients of 50–70%, on terrain classified in terrain stability hazard mapping as Class III, or stable (Jordan 2001). In the Shuswap Highlands, GoS landslides generally occur on terrain mapped as terrain stability hazard Class IV, or potentially unstable.[1] Terrain mapping is a very useful tool, both in identifying the potential hazard and the terrain characteristics.

Gullies are frequently a factor in GoS slides. Landslides may initiate as gully side wall failures, or as open slope debris slides that enter a gully some distance downslope and become channelized debris flows. The presence of gullies, even those starting hundreds of metres downslope of the road or slope break to steeper terrain, can greatly increase both the likelihood of landslide initiation and the potential landslide runout distance.

In assessing existing GoS landslides, one of the main criteria for judging the pre-failure slope sensitivity is the amount of water diverted onto the slope to cause the failure. For example, sites have been observed with relatively minor cutslope seepage interception, and culvert spacing as low as 50 m, where significant landslides have occurred downslope of almost every culvert. Obviously, this area and areas with similar terrain are only marginally stable, and, depending on the risk, development must proceed very cautiously, or not at all.

Conversely, it has been observed that significant landslides have been caused by the cumulative concentration of up to 20 ha of hillslope drainage to a single culvert (Figure 3), or the total diversion of a stream onto the failed slope (Figures 4 and 5). In these cases, it was concluded that the factor of safety of these slopes was not particularly low, and harvesting with adequate forest road and trail drainage management would not result in a significant landslide hazard.

Determining the flow paths and size of water diversions responsible for landslides may require traversing many hundreds of metres upslope of the slide to the road or trail drainage source, and then tracing the drainage concentration and interception that occurred along and above that source, as shown in Figure 3.

Once the downslope sensitivity to introduced drainage has been established for the terrain type in question, there can be a qualitative statement of the likelihood of a downslope landslide and its potential magnitude, given some quantity of introduced water required to initiate that slide. With an

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[1] In the Salmon Arm Forest District, much of terrain stability hazard mapping identifies terrain with normal morainal and colluvial soils, and slope gradients > 60%, as Class IV or IVR, or potentially unstable (EBA Engineering Consultants Ltd. 1997–2000).

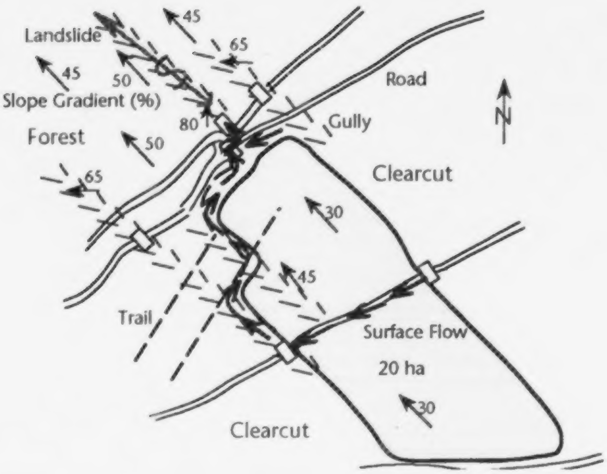


FIGURE 3 *Hillslope drainage concentration from a 20-ha area.*

understanding of the other site and development factors, the necessary recommendations can be made to prevent that amount of water from being directed onto the slope.

Site Moisture Regime

The site moisture regime is the form and magnitude of hillslope runoff that a proposed road or trail will encounter. While it may seem obvious that a wetter site will have a higher hazard than a drier site, this may not always be so. Previously in this paper it was shown that the empirical evidence suggests that drier regions may be more susceptible to GoS landslides than wetter ones. However, at a locally wetter site in a drier region, there may be more moisture available to be intercepted by a road or trail, and thus a higher hazard.

Gentle-over-steep slides have been associated with varying climatic inputs, from large, relatively infrequent rain and/or snowmelt events, to relatively normal spring snowmelt rates. The climatic input required to initiate a landslide can be less critical than the magnitude of runoff interception and concentration.

Particularly on gently sloping terrain, road drainage structures have traditionally been designed to prevent road prism failures such as culvert washouts. However, ditches and culverts that can safely pass a 50- or 100-year runoff event may easily divert enough hillslope runoff during much smaller events to cause a GoS landslide. Generally, if the downslope area has been determined to be potentially unstable, and the proposed road prism and grade have the potential to intercept and concentrate flow, a GoS landslide is possible.

During a site assessment, it is important to note the types and location of potential slope drainage elements. These can include permanent or seasonal streams, seepage sites, dry swales or gullies, and the depth to an impermeable layer on uniform open slopes.

Upslope drainage can be in a natural, undisturbed state, or there can be abundant upslope skid trails and roads that have intercepted, concentrated, and redirected drainage, often for considerable distances (Figure 3).

In assessing the moisture regime at the road alignment, the connections to any existing upslope developments should be determined. Particularly during road upgrading and deactivation, which occur in developed areas, alterations to upslope drainage patterns should be investigated. A drainage plan is often required, both of natural and development-related upslope drainage paths. A drainage plan methodology is discussed elsewhere in this publication (Green and Halleran 2002) and is an important tool in managing GoS landslide hazards.

Preparing a drainage plan can require traversing many hundreds of metres upslope of the site being investigated, and can take as much time as assessing the downslope safety factor. It may also show that it is better to correct redirected upslope drainage, rather than attempt to manage artificially high flows at the road alignment being assessed.

An understanding of the volume, type, and location of upslope flow paths is used to determine how the hillslope drainage could interact with the prism and alignment of proposed or existing roads.

Road Prism Conditions

The different types of hillslope drainage create different drainage interception problems at the road prism. Stream crossings have the potential to divert the largest flow volumes, and undersized or poorly installed cross-drains have caused numerous GoS landslides. Figure 4 shows a stream and culvert under normal spring freshet conditions on an active forest road. It is apparent that under extreme runoff conditions the capacity of this culvert would likely be exceeded. It may be that it was believed that the road prism was not at risk, because excess flow could escape down the ditch at the top of the picture; this is precisely what occurred. Peak streamflows overtopped and eroded the ditch block, travelled 300 m down a 10–15% ditch grade, washed out another culvert, and exited the road. All flow infiltrated into a 100 m wide flat bench a short distance downslope of the road. The landslide shown in Figure 5 initiated just below the bench on an 80% slope, 100 m directly downslope of where the redirected flow left the road.

In GoS landslide–prone terrain, designing drainage to protect the road prism while allowing excess flows to be diverted out of natural drainage paths can increase the landslide hazard. Road drainage structures should be

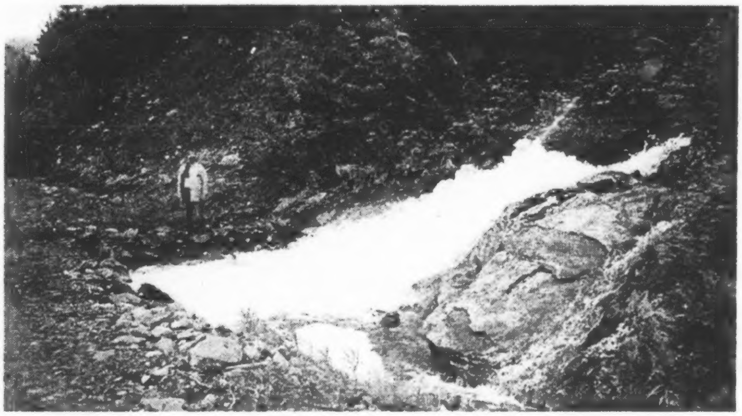


FIGURE 4 *Large seasonal stream flow, relative to a 600-mm culvert. Peak flows escaped down the ditch towards top of photo, causing the landslide shown in Figure 5.*

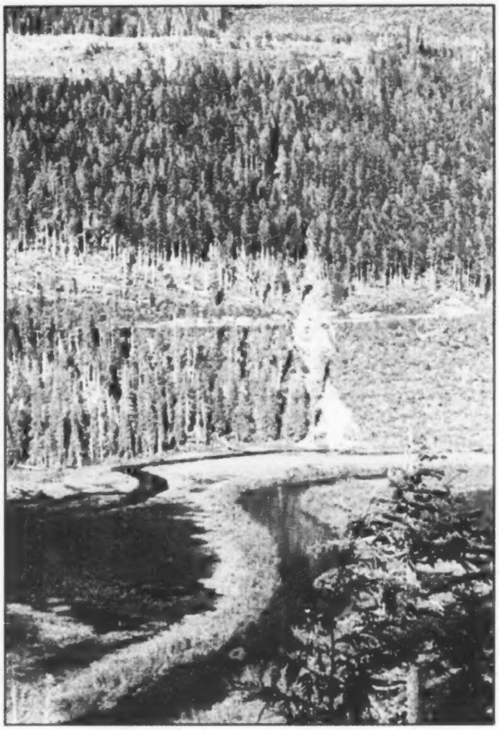


FIGURE 5 *Gentle-over-steep landslide caused by undersized culvert and stream diversion.*

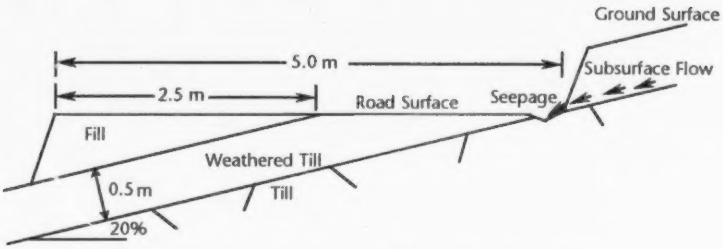
designed to both protect the prism and prevent drainage diversion.

In relatively minor swales or gullies, failure to recognize the potential for seasonal flows can cause similar problems. Often there is little or no evidence along the road alignment of the existence of upslope drainage diversions that could deliver abnormally large flows to the road in an otherwise dry swale, with the result that road drainage structures, including culverts, cross-ditches and ditch blocks, have been under-designed.

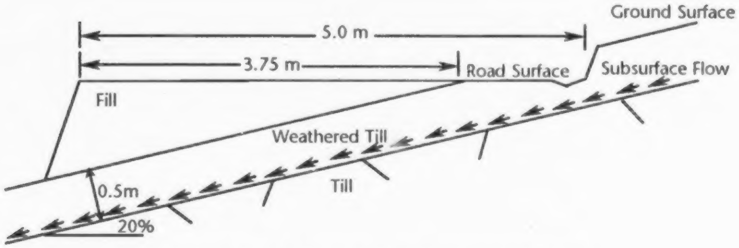
On uniform slopes, it may be necessary to understand the near-surface soil layering to be able to predict what effect a proposed road cut will have on interception of subsurface drainage. GoS landslides have been initiated by nothing more than normal ditch lengths intercepting seasonal subsurface groundwater flow from cutslopes that appear dry for most of the year.

For example, a common soil structure in the southern Interior is a 0.5 m thick, loose, relatively permeable weathered till overlying dense till. Generally, natural subsurface drainage on well-drained forested hillslopes in the southern Interior can be expected to be confined to relatively narrow band at the base of the permeable layer, due to the rapid infiltration and soil drainage effected by macropores (root casts, animal burrows, etc.). A thin perched water table forms at the base of the permeable upper weathered till layer (Figure 6).

Simple trigonometry can be used to calculate the expected impact of the proposed road prism on subsurface drainage, as shown in Figure 6a. Minimizing the road width is the simplest way to reduce the road prism incision into the hillslope, and avoid intercepting subsurface flow. Where this is not feasible, widening the fill portion of the road prism can achieve the same



a. Balanced bench construction on a 20% gradient slope with a 5.0 m wide road prism and a 0.5 m depth to impervious layer.



b. On the same slope, with road fill width increased by 1.25 m.

FIGURE 6 *Road prism geometry and subsurface drainage interception.*

effect. Under the conditions shown in Figure 6, increasing the fill width by 1.25 m will increase the depth to the impervious layer by 0.35 m, making it unlikely that the cutslope will intercept significant subsurface flow (Figure 6b). On steeper slopes, this technique will work if there is a thicker permeable soil layer.

In the Figure 6 example, the fill volume will approximately double and will require importing fill material. Depending on the overall cut and fill mass balance along the road alignment, increasing the fill width to reduce the cutslope height may be cost-effective in preventing intercepting subsurface drainage and reducing the GoS landslide hazard.

Road Grade Configuration

The road grade is defined as the road surface or ditch slope gradient along the road alignment profile. Long, continuous road grades can always create the potential for drainage concentration and redirection. However, if there is no road grade to redirect intercepted flow, there will be no increase in landslide hazard due to drainage diversion.

A rolling grade, with the road grade upslope in both directions away from cross-drains, limits the length of road along which drainage can be concentrated. Even if culverts in the grade dip should fail, streamflow could not escape along the alignment, but would be retained in its natural drainage path.

If the road location is preliminary at the time of the assessment, and has not been traversed, grades will have to be measured through critical areas. If the alignment has been traversed, the assessor should obtain the traverse notes, or preferably the road plan and profiles. With good road grade information and terrain stability hazard mapping, potential problem areas can be identified in the office, allowing for more efficient use of field time. If there is no preliminary alignment at the time of the traverse, there may be an opportunity to use road grade design to reduce a potential GoS landslide hazard.

If there is a potential downslope hazard and a consistent road grade, the level of attention given to drainage design, installation, maintenance and deactivation should increase accordingly.

Slope Drainage Connectivity

An important and difficult question in assessing GoS landslide hazards is how far downslope from development should the slope stability investigation be concerned with. That is, how far downslope of a road or trail can a GoS landslide be initiated?

In the Columbia Mountains, GoS landslides initiating 600–800 m downslope of the water source have been reported (P. Jordan, B.C. Min. For., Nelson Forest Region, pers. comm., 1999; BGC Engineering 2001). In the Shuswap Highlands, the author has observed GoS landslide initiation commonly occurring at slope breaks located from a few metres up to approximately 200 m downslope of the road on open slopes, and up to 300 m in confined swales or gullies. With a large enough drainage diversion and sensitive enough downslope terrain, much greater distances are possible and have been reported (C. VanBuskirk, Terratch Consulting Ltd., pers. comm., 2002).

The runoff, infiltration, and pore pressure interactions downslope of the road are probably the least well understood component of GoS landslide processes. Once the redirected water leaves the road, it is travelling over or through gentle to moderate-gradient terrain. Depending on the volume of flow and the infiltration characteristics of the slope, redirected water may infiltrate a short distance downslope of the cross-drain outlet, travel as overland flow some distance before infiltrating, or never totally infiltrate before joining some downslope watercourse. Freeze (1987) noted that "because the hydraulic conductivity of surface soils varies so greatly, individual hillslopes often exhibit different runoff-generating mechanisms at different places during the same storm, or at the same place during different storms" and complexities of geologic structure, layered soils, and saturated–unsaturated interactions "can have significant impacts on infiltration rates and growth and decay of pore pressures through time."

So while there are many possible road drainage, slope runoff, and infiltration process interactions, it is likely that in a particular region, most GoS landslides will be the result of a small set of those possibilities. Research into existing landslides is needed to determine what are the terrain and hydrologic parameters influencing the downslope distance over which redirected water could have an effect.[2] Until we have a better understanding of the way introduced water behaves between the development and the landslide, most assessments will depend on the comparative assessment method discussed earlier in this paper.

The following discussion of subsurface process uses one possible model for this behaviour. It is intended to illustrate one of the downslope drainage issues to be considered when assessing the GoS landslide hazard.

In the Shuswap Highlands, many GoS landslides occur where the distance between the road and slope break is less than 100 m. Fewer landslides occur when the distance is between 100 and 200 m, and fewer yet when the distance is between 200 and 300 m. Over 300 m, only isolated incidents are known. The fact that the number of landslides decreases with increasing distance between water source and slope break suggests that some dissipation of water occurs as the water moves between the gentle terrain between the road and steeper slopes. This may be from infiltration losses to deeper groundwater recharge, or from lateral dispersion (Figure 7).

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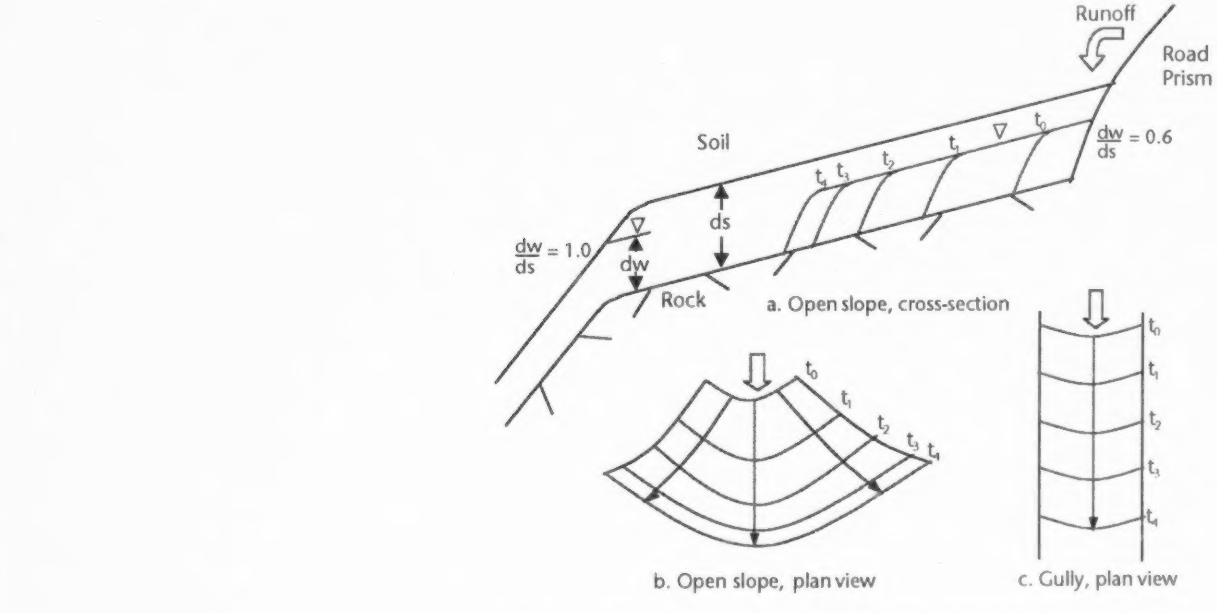
[2] Research into this and other GoS landslide issues will be carried out in selected areas in the southern Interior over the next few years (D. Stead, Simon Fraser Univ., Dep. Earth Sciences, pers. comm., 2001).

It is assumed that at the start of a runoff event (t_0), most of the water exiting a culvert infiltrates rapidly into the soil column a short distance downslope of the cross-drain. This occurrence is commonly observed above GoS landslides in the Shuswap Highlands. Some new value of *dw/ds*, which is higher than that which the slope has historically experienced, develops just downslope of the road. As time progresses, this saturated front, or groundwater mound, extends downslope through successive equal time intervals ($t_1 - t_0 = t_2 - t_1$, etc.).

In relatively uniform soils, a lateral hydraulic head gradient will cause the saturated front to spread out on both sides of the main flow path (Figure 7b). Assuming a steady-state water supply from the cross-drain for the duration of a runoff event, less water will be available to supply the downslope movement of the elevated saturated front because some water flows laterally. The distance that the front extends will decrease for successive equal time intervals (Figures 7a and 7b). In this way, the water table mound disperses laterally. Depending on the magnitude and duration of the runoff event, and the distance between water source and slope break, the critical elevated water table level may or may not reach the slope break.

Note that if the elevated water table reaches the slope break, not only is the slope steeper, but the soil is likely to be thinner on the steeper slope (Jordan 2001). In the thinner soils, the ratio *dw/ds* increases, shear strength is reduced, and the landslide hazard increases.

Figure 7c shows a plan view of the progress of the water table mound in a confined swale or gully, where the topography prevents lateral dispersion of



a. Open slope, cross-section

b. Open slope, plan view

c. Gully, plan view

FIGURE 7 *Subsurface drainage downslope of a cross-drain during an extreme runoff event.*

subsurface flow. Without lateral dispersion, the water table mound can travel farther in a given time interval than on an open slope. With only subsurface flow in a gully downslope of a road, the elevated water table will be more likely to reach a distant slope break. Therefore, a gully may or may not be the preferred place to direct concentrated road drainage in this type of terrain.

Note that in this case we are talking about relic swales or gullies where the water table generally does not reach the ground surface, and saturated overland flow seldom or never occurs, unlike gullies that carry seasonal or permanent streams. In the drier Plateau and Highlands regions, relic "dry" swales or gullies are common (Figure 8). They may be less so in the wetter Columbia Mountains to the east. They probably formed during periods of extreme runoff volumes following deglaciation, or other wetter climatic intervals, thousands of years ago. These types of gullies can be identified by a uniform forest cover, a well-developed "A" soil horizon, and no evidence of sediment or litter movement by surface flows in the bottom of the feature.

Note that not only can a gully extend the downslope distance that redirected drainage can travel, but because in relic gullies *dw/ds* has generally been << 1.0, the gully sideslopes and base may themselves be sensitive to water table and pore pressure increases.

It is common practice to routinely culvert swales and gullies along a road alignment. Where this simply maintains a natural drainage path across the road prism, it is usually good practice. Where the culvert is also the potential exit point of concentrated road drainage, the situation can be more complex. Where other factors indicate that there is a potential drainage-related landslide hazard, some understanding of the subsurface soil saturation and pore pressure history is warranted; this can often be deduced from existing site conditions. This does not mean that swales and gullies may not be the preferred place to direct concentrated flows. Assessing each situation will require knowledge of regional terrain and hydrologic characteristics, as well as the specific site conditions.

In any terrain, probably the worst place to direct road drainage is towards steep sideslopes of a gully containing a stream. GoS debris slides initiating

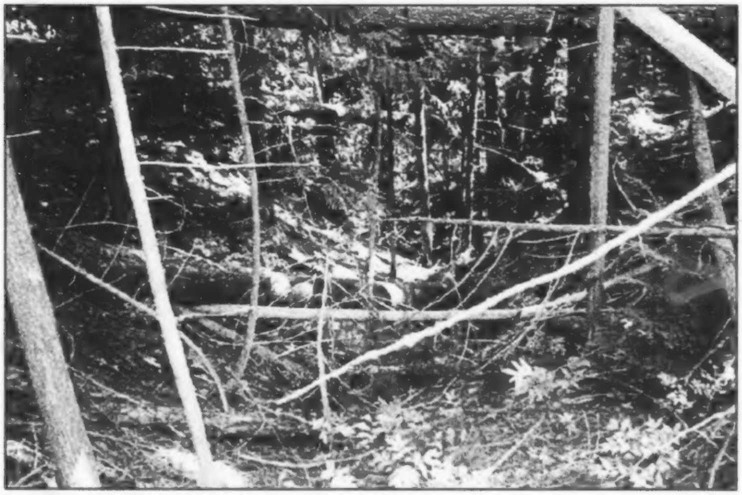


FIGURE 8 *Typical relic "dry" gully in the Shuswap Highlands near Sicamous, B.C.*

on steep gully sideslopes can initiate debris flows by impacting the saturated channel, and have caused the largest and most destructive landslides in the southern Interior of British Columbia.

MANAGEMENT STRATEGIES IN GOS TERRAIN

Strategies to reduce the GoS landslide hazard can be grouped under three general headings. The choice of a particular action, and the extent to which it is implemented, will depend on operational constraints, the downslope hazard, and downslope and downstream risks. In general, the three strategies are:

- to eliminate hillslope drainage interception and concentration;
- to limit drainage interception, concentration, and redirection; and
- to limit the time during which potential drainage disruption can occur.

Eliminate Hillslope Drainage Interception and Concentration

All GoS landslide problems start when hillslope drainage in some form is intercepted and concentrated by a road or trail. When downslope terrain is only marginally stable, the management strategy may have to be one of no potential drainage interception or concentration. Sites where small drainage concentrations can initiate landslides are not common, but need to be recognized where they occur, particularly where downslope risks are high. In the extreme case, this could mean that no development should occur in a location that could impact sensitive downslope terrain. Otherwise, it means that the road alignment and prism are designed so that there is little or no chance of intercepting or concentrating drainage. Permanent and seasonal stream crossings should be designed conservatively; this may entail a detailed upslope investigation of natural or altered drainage contributing areas (Green and Halleran 2002).

Interception of subsurface drainage may be avoided by narrowing the road width or widening the road fill (Figure 6), or by installing continuous subgrade drainage. In these cases, ditches and culverts may not be desirable, and in certain situations it can be a reasonable strategy to not install them, both to preclude drainage concentration and to minimize the road prism width and cutslope height. In all these cases, road surface drainage will likely have to be managed by avoiding long continuous grades, or by installing water bars. On fairly flat grades, road outsloping can manage both hillslope and road surface runoff. Outsloping or ripping the compacted road surface may be necessary before other road deactivation works occur.

Limit Drainage Interception, Concentration, and Redirection

Where the downslope sensitivity is less but still of concern, drainage structures and their placement can be designed to minimize the occurrence of significant interception, concentration, and redirection.

Interception can be minimized by ensuring that all upslope drainage sources are identified, and permanent and seasonal stream crossings designed conservatively. All potential seepages should have cross-drains, and road widths and cutslope heights should be minimized. Field assessments should ideally be done during the spring runoff season, as many runoff features flow for only a few weeks each year, and may not be evident during the dry season. A follow-up site visit may be required after construction to check for seepage locations and drainage diversions that were not apparent before construction.

Drainage concentration down the road grade can be minimized by reducing the distance between cross-drain structures (culverts, cross-ditches, and water bars). Minimum cross-drain spacing should be specified to the extent required by downslope sensitivities, site moisture conditions, and other factors, not solely by road gradient (as is common practice). Cross-drains should have back-ups (ditch blocks and/or water bars) that are designed, installed, and maintained to prevent flow escaping down grade in the event of cross-drain failure—even at the expense of the road prism. Designing the alignment grades so that there is a grade dip will reduce the likelihood of cross-drain flow escaping down the road grade.

Swale and gully characteristics and their connection to steeper downslope terrain should be examined carefully before cross-drain locations are selected, (see Figure 7). Where it is operationally feasible, or where downslope conditions dictate, the road alignment can be moved to a location that increases the distance between the road and steeper, marginally stable slopes.

Limit the Time during Which Potential Drainage Disruption Can Occur

Gentle-over-steep landslides in the southern Interior commonly occur during spring snowmelt (Jordan 2001). In the Shuswap Highlands, they have occurred less often during relatively infrequent, moderate duration (days to weeks long) early summer precipitation, and rarely during early fall precipitation. Outside these times—particularly during the summer dry season—there is the opportunity to build roads and trails above high-hazard or high-risk slopes. If the road or trail is then deactivated and all natural drainage paths restored before the onset of the next wet season, the hazard or risk can be minimized.

Similarly for more stable downslope areas, it may be reasonable to install roads with drainage structures that will disrupt natural hillslope drainage to some extent, if the period they will be in place is short relative to the frequency of an extreme precipitation event judged to be large enough to trigger a slide. For example, site and development conditions at a particular site may indicate that a rare (50- to 100-year) climatic event would be required to cause a GoS landslide. If a road is planned for only 2–3 years between construction and deactivation, the probability of such an event occurring during the period of active use is low. Depending on the downslope risk, it may be reasonable to construct, use, and deactivate a road within that short period.

It will require a degree of familiarity with local landslide occurrences and antecedent climatic conditions, existing slope sensitivities, and downslope risks in an area to conduct this type of risk analysis. However, it is my experience that with more detailed hazard and risk analysis, not only are potential liabilities better managed, but savings in reduced construction, maintenance, and lost opportunity costs far outweigh assessment costs.

CONCLUSIONS

Gentle-over-steep landslides are caused by interactions between terrain, hydrologic, and development factors. An assessment of potential GoS landslide hazards requires evaluating each, and integrating how they could interact with each other. The skills required include knowledge of landslide processes, geomorphology, surface and subsurface hillslope hydrology, and forest road design and construction.

Until there is adequate research and a better understanding of parameters controlling GoS landslide occurrence, hazard assessment will rely primarily on comparing the site under consideration to other sites with similar terrain and developments. It would be prudent for the assessor to either have extensive experience in a particular area, or to conduct a thorough investigation of the relevant surrounding terrain as part of the assessment.

Gentle-over-steep landslides are fundamentally about the movement of water—upslope, along, and downslope of the road or trail in question. Thus much of the investigation should focus on terrain and hydrologic conditions some distance both up- and downslope of the development, as well as on how the proposed development will connect the two. The better the understanding of these processes, the more effective, and cost-effective, management of these landslide hazards and risks will be.

ACKNOWLEDGEMENTS

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REFERENCES

Anderson, W.P.D., P.W. Clarke, E.A. Fuller, T.R. Giles, D.R. Lister, R.D. Winkler, and P.J. Woods. 1997. Hummingbird Creek debris event July 11, 1997. Inter-agency report. B.C. Min. Environ., Lands and Parks; B.C. Min. For.; B.C. Min. Transp. and Highways; and B.C. Min. Attorney General, Victoria, B.C.

BGC Engineering. 2001. Albreda Mile 110 to 117. Assessment of risk from proposed forestry developments. Report prepared for CN Rail.

British Columbia Ministry of Forests. 2000. Forest road regulation. B.C. Reg. 106/98. *Forest Practices Code of BC Act.* Consolidated to April 10, 2000.

British Columbia Ministry of Forests. 1999. Mapping and assessing terrain stability guidebook. 2nd ed. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

Dobson Engineering Ltd. 1997. Investigation into the cause of the Hudson Creek debris torrent of May 15, 1997. Report prepared for B.C. Min. For., Salmon Arm Forest District, Salmon Arm, B.C.

EBA Engineering Consultants Ltd. 1997–2000. Detailed and reconnaissance terrain mapping, Salmon Arm Forest District. Reports prepared for B.C. Min. For., Salmon Arm Forest District, and Federated Co-operatives Limited.

Environment Canada. 1993. Canadian climate normals, 1961–1990, British Columbia. Atmos. Environ. Serv., Ottawa, Ont.

Freeze, R.A. 1987. Modelling interrelationships between climate, hydrology and hydrogeology and the development of slopes. *In* Slope stability: geotechnical engineering and geomorphology. M.G. Anderson and K.S. Richards (editors). John Wiley & Sons, New York, N.Y. pp.381–403.

Green, K. and W. Halleran. 2002. Drainage plans: A comprehensive planning tool in high risk terrain *In* Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proc. P. Jordan and J. Orban (editors). Nelson, B.C., May 23–25, 2001. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. B.C. Dep. Mines and Petroleum Resour., Victoria, B.C. Bull. 48.

Horel, G., B. Chow, B. Graham, C. Smith, B. Suzer, and D. VanDine. 1996. Discussion paper—Review of reports prepared by engineers and geoscientists in the forest sector. ASPECT, Division of Engineers and Geoscientists in the Forest Sector Newsletter, Assoc. Professional Engineers and Geoscientists of B.C. Vol. 1(1).

Jakob, M. 2000. The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. Catena 38:279–300.

Jordan, P. 1999. Presentation at Assoc. Professional Engineers and Geoscientists of B.C. Annual Conf., Oct. 21–23, 1999, Victoria, B.C.

———. 2001. Regional incidence of landslides. *In* Proc. Watershed Assessment in the Southern Interior of British Columbia. D.A.A. Toews and S. Chatwin (editors). B.C. Min. For., Res. Br., Victoria, B.C. Work. Pap. 57/2001, pp. 237–47.

Schwab, J.W., P. Clarke, R.J. Reimer, W.R. Mitchell, and D.A Dobson. 1990. Investigation into the cause of the destructive debris flow, Joe Rich – Belgo Creek areas, June 12, 1990. B.C. Min. For., Penticton Forest District, Penticton, B.C.

Skempton, A.W. and F.A. DeLory. 1957. Stability of natural slopes in London clay. *In* Proc. 4th International Conf. Soil Mechanics and Foundation Engineering, London, U.K. Vol. II, pp. 378–81.

Turner, K., D. Erickson, D. Vandine, and P. Mitchell. 2001. Should we change the way we carry out TSFAS? Current practices and expectations. ASPECT, Division of Engineers and Geoscientists in the Forest Sector Newsletter, Assoc. Professional Engineers and Geoscientists of B.C. Vol. 6(4).

Landslide Frequencies and Logging on Vancouver Island: An Analog Showing Varied yet Significant Changes

R.H. GUTHRIE

ABSTRACT

Despite a long history of landslide research in British Columbia, there remain few data on the actual change in rates of landslides following harvesting activities other than from the Queen Charlotte Islands and the Clayoquot Sound region of Vancouver Island. The application of these data to other areas in British Columbia is problematic. This paper discusses implications of the results of a study of three watersheds on Vancouver Island: Macktush Creek, Artlish River, and Nahwitti River watersheds. Some 363 landslides, from 0.02 to > 1 ha, were identified in three watersheds from air photographs, beginning at a date that essentially preceded logging up to the present. Landslide frequencies increased in Macktush Creek, Artlish River, and Nahwitti River by approximately 11, 3, and 16 times, respectively. Two to 13 times more landslides reached streams following logging; most of these were between 0.2 and 1 ha. Landslide density analyses produced variable results, ranging from 2.4 to 24 times increases in number of landslides. Road landslide frequencies increased by 27, 12, and 94 times for Macktush, Artlish, and Nahwitti, respectively. Landslide frequencies need to be determined for many more watersheds to provide better information on the effects of logging activities on both Vancouver Island and the Interior of British Columbia. It is against this baseline that geoscientists and geotechnical engineers practising in the forest sector can measure their successes at reducing the impact of landslides in British Columbia.

INTRODUCTION

The relationship between landslides and forest harvesting in British Columbia is not a new topic. Studies have examined the causes at several different scales for decades, particularly on the Coast. These studies include regional inventories (Rood 1984; Sauder et al. 1987; Gimbarzevsky 1988; Millard 1999), watershed-type studies (Thomson 1987; Hartman et al. 1996; Jakob 2000), and thousands of individual landslide reports. Studies have focused on: causative factors (Schwab 1983; Millard 1999), frequency of landslides (O'Loughlin 1972; Howes 1987a; Guthrie 1997; Thomson 1998), recovery (Smith et al. 1986), and terrain types that may be more prone to landsliding (Howes 1987a, 1987b; Howes and Sondheim 1988; Rollerson 1992; Rollerson et al. 1998; Jordan 2002; Millard and Rollerson 2002). It is perhaps ironic that despite the studies to date, we remain largely unaware of the effects of harvesting practices on the frequency of landslide occurrence in British Columbia watersheds. This discussion paper is based substantially on a paper submitted to *Geomorphology* (Guthrie 2002) and readers are referred to it for complete details of these results.

There is a global and local perspective that the occurrence of landslides is generally undesirable. Geoscientists and geotechnical engineers refer to the cost of landslides in terms of lives, property, and environmental values. In Canada, estimates have been made that we spend $50 million (1989 dollars) a year (Schuster 1996) on landslide costs, and about five people per year lose their lives to landslides. Indirect costs to resources are more difficult to measure but include loss of forest productivity, reduced real estate values, and loss of commercial or sport fisheries production. Schuster (1996) claims that despite improvements in our knowledge base, global landslide activity is increasing. He attributes the increase to three factors: increased (urban) development in landslide-prone areas, climate change, and deforestation of landslide-prone areas.

Geoscientists, geotechnical engineers, and related professionals are part of a field of professionals trying to reduce the impacts of landslides on society by mitigative and preventative methods. Terrain stability field assessments, watershed assessments, gully assessments, and road assessments are carried out to reduce landslide frequencies. A measure of change in landslide frequency is required to determine the effectiveness of preventative measures. Unfortunately, natural rates of landsliding are not commonly known, so progress is difficult to evaluate. This is a major oversight that inhibits the ability to gauge successes of any particular prevention program.

This paper documents the increase in landslide frequencies associated with logging activities in three watersheds on Vancouver Island. It is expected that the results may be analogous to those in similar watersheds. At a minimum, it illustrates the need for better information about natural and post-logging frequencies across British Columbia.

STUDY AREA

The watersheds of Macktush Creek, the Artlish River, and the Nahwitti River on Vancouver Island were examined in this study (Figure 1).

Vancouver Island is predominantly rugged, having been subjected to multiple glaciations in the Pleistocene, and elevations range from sea level to 2200 m. The Vancouver Island Ranges, steep mountains composed of volcanic and sedimentary rocks intruded by granitic batholiths, make up the central and largest part of Vancouver Island (Holland 1964; Yorath and Nasmith 1995). Deep fiords and long inlets dissect the western coast, and rolling terrain and low relief of the Nahwitti Lowland characterize the northern tip of the island, most of which falls below 600 m above sea level.

Precipitation varies widely from less than 700 mm/yr around Victoria (Environment Canada 1993) to nearly 6000 mm/yr on the west coast (Chapman 2000). The watersheds in this study receive between 2000 and 4000 mm of rain per year, the Artlish River watershed being the wettest and Nahwitti River watershed the driest.

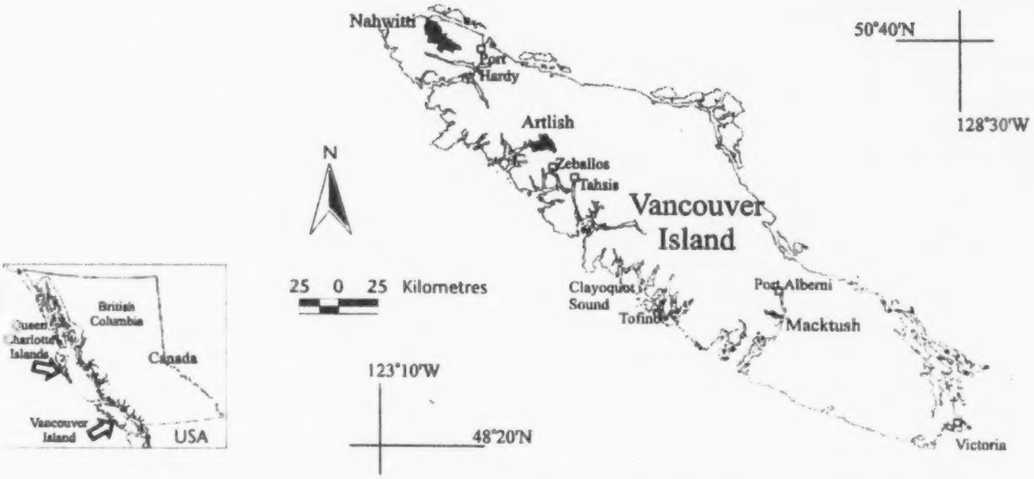
Nahwitti
Port Hardy
50°40'N
128°30'W
Artlish
N
Zeballos
Tahsis
Vancouver Island
25 0 25 Kilometres
Clayoquot Sound
Tofino
Port Alberni
Macktush
British Columbia
ueen
harlotte
Islands
Canada
123°10'W
48°20'N
Vancouver Island
USA
Victoria

FIGURE 1 *Location map showing the three study areas on Vancouver Island (from Guthrie 2002).*

Macktush Creek drains a small (28 km²) narrow watershed into the Alberni Inlet, approximately 12 km south of Port Alberni. Much of the watershed is steep, with elevations ranging from 1100 m to sea level. Logging began in the Macktush watershed early in the 20th century but was initially limited to a small portion of the estuarine fan until the mid-1970s. To date, 50% of the total watershed area has been harvested, although much of the area of earlier logging is in recovery. Over 75 km of roads have been constructed in the Macktush basin (2.7 km/km²) and 40% of those roads have now been deactivated, most following a prescribed program in 1996.

The Artlish River drains a 125-km² watershed into the Tahsis Inlet, about 25 km northwest of Zeballos. Much of the Artlish watershed is mountainous, with steep walls and a broad valley floor. Elevations range from sea level to 1540 m. Logging began in the Artlish basin in the 1970s. To date, approximately 21% of the watershed has been logged, and earlier harvested blocks are in some state of recovery. Approximately 177 km of roads have been constructed for a density of 1.4 km/km². At least 18% of roads have been deactivated.

Nahwitti River drains a large (229 km²) watershed into Queen Charlotte Sound about 26 km north of Port Hardy. It lies completely within the Nahwitti Lowland and so is characterized by low relief, rounded hills, lakes, and bogs throughout the watershed. Most of the Nahwitti basin is below 600 m elevation, and approximately 32% of the watershed is covered by bog plateaus. Only about 2.5% of the watershed has slopes > 31° (60% slope). Except for a small wartime entry in the early 1940s, harvesting began in the watershed in the mid- to late 1960s. Approximately 23% of the watershed has been harvested and is in varying stages of recovery. Approximately 213 km of roads have been constructed for an overall density of 0.9 km/km². The roads are concentrated in the southern portion of the watershed, however, and local densities are considerably higher. There are no roads across the bog plateaus.

Across the three watersheds, 363 landslides ranging in size from 0.02 to > 1 ha were identified on aerial photographs in roughly 15-year intervals ranging from 1955 to 1996 (Guthrie 2002), and on the ground in 1999 or 2000. Landslides < 200 m² were observed, particularly at road edges, but were excluded from the study because they could not be identified consistently and probably not at all under forest canopy. Landslides smaller than 500 m² were also difficult to define in forested terrain; while a few were identified, it is likely that many were missed. Few landslides less than 500 m² were recorded in either logged or unlogged terrain, and results are not expected to be substantially affected. Landslides were plotted cumulatively and frequencies were determined by counting the number of new landslides per interval (landslides per year). Results indicated that landslide frequencies went up 11 times in the Macktush Creek watershed, 3 times in the Artlish River watershed, and 16 times in the Nahwitti River watershed compared with the natural rate over the period of record (Figures 2–4).

Previous studies of landslide frequency have examined the number of landslides by cause, as a function of the total area, or compared the number of landslides per area logged with the number of landslides per area unlogged (Rollerson et al. 1998; Jakob 2000). Although frequency is somewhat implicit in these analyses, they are actually measures of changes in landslide density. Density changes can be calculated looking at a single set of air photographs. However, this measure tends to dilute the impact of post-logging landslides by comparing landslides limited by the period of development, with natural landslides occurring over a longer period.

Jakob (2000) applied correction factors to landslide density data of 40 and 60 years for natural landslides (an estimate of the length of time beyond which a debris slide was unlikely to be identified) while post-logging landslides were corrected by dividing by the period of development in years. He

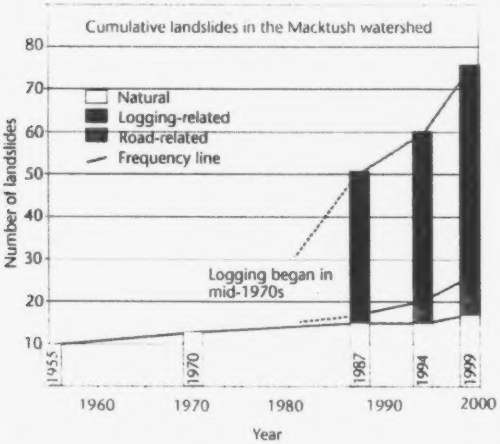

FIGURE 2 *Cumulative landslides in Macktush Creek watershed. The natural rate of landslides appears to be about one every 5 years. The post-logging average rate is 2.2 landslides per year, an increase in frequency of 11 times (diagram from Guthrie 2002).*

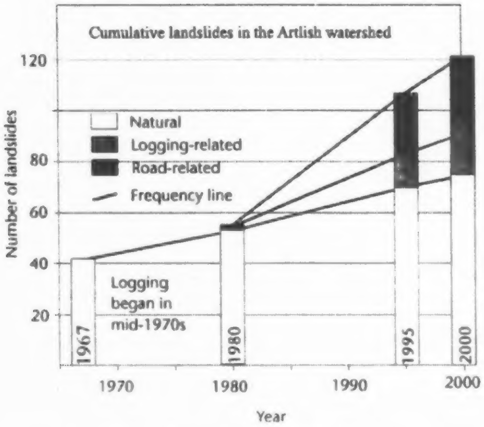

FIGURE 3 *Cumulative landslides in Artlish River watershed. The natural rate of landslides appears to be about one per year. The post-logging average rate is 3.25 landslides per year, an increase in frequency of about 3 times (diagram from Guthrie 2002).*

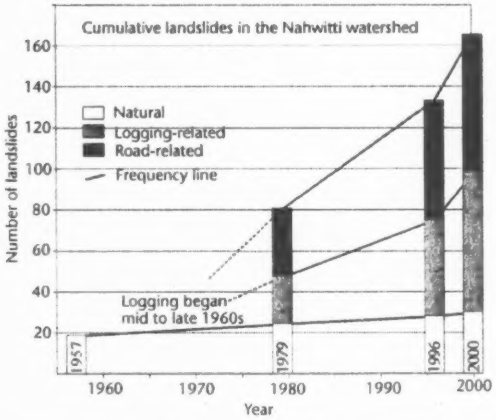

FIGURE 4 *Cumulative landslides in Nahwitti River watershed. The natural rate of landslides appears to be about one every 4 years. The post-logging average rate is 4 landslides per year, an increase in frequency of about 16 times (diagram from Guthrie 2002).*

used these corrections to determine that post-logging landslide frequencies increased in Clayoquot Sound by 18–26 times. Table 1 shows a comparison of landslide frequencies and densities for the three watersheds on Vancouver Island using each method.

Variable results given in Table 1 show some of the weaknesses of looking at changes in landslide densities. In the Macktush watershed, even with the correction factors, the increase in landslide density underestimates the actual increase in frequency of landslides. In this case a relatively large area logged (50% of the watershed), most of which is on ground < 60% slope, negatively biases the results. In fact, the landslides that follow logging activity are focused on the smaller steeper portion of that landscape. Conversely, in the Nahwitti watershed, a relatively small portion of the landscape has been

TABLE 1 *Results of frequency and density analysis in Macktush Creek, Artlish River, and Nahwitti River (adapted from Guthrie 2002)*[a]

Watershed	Frequency (landslides per unit time)	Density (landslides per unit area)	Density (temporal correction of 40 years for natural landslides and period of development for other landslides)	Density (temporal correction of 60 years for natural landslides and period of development for other landslides)
Macktush Creek	11	3.5	5.6	8.5
Artlish River	3	2.4	4	6
Nahwitti River	16	15	18	24

a Results indicate times increase following harvesting activities compared with the natural state for the period of record.

logged, including almost all slopes > 60% (much of the flat areas are inoperable bogs). Unfortunately, local geology in combination with the harvest and road-building activities resulted in substantial instability on those and adjacent slopes. The density scores are similar to those of Jakob (2000) when corrected for ability to discern natural events for a longer period than the period of development, but more than the actual increase in landslide frequency. The corrections serve to exaggerate the disparity in landslides per unit area of land use. This is similarly true in the Artlish River watershed.

That being said, in combination with actual frequency changes, the densities complete the picture of logging effects rather well. The results indicate that the rate of landslides has gone up considerably in all three watersheds (albeit differently in each). Not only has the landslide frequency gone up, but landslides are concentrated in a small portion of the landscape (increased densities) and that portion is logged.

If densities alone are used to determine the impact of harvesting, the study area should be stratified by slope classes, therefore allowing better comparisons of logged and unlogged areas.

Other studies have also shown substantial increases in landslide density. Rood (1984) recorded an increase in landslides following harvesting of 34 times, and Schwab (1998) recorded increases of 15 times in the Rennell Sound area.

Density changes are useful when looking at the impact of particular features or practices that do not occupy a large portion of the landscape. To this end, landslide densities on roads were compared with landslide densities in the natural condition. The total area of a watershed designated as road was determined using an average road width of 20 m. Landslides connected to roads were summed and divided by the area determined to be road, and compared with the number of natural landslides divided by the unlogged area. The results indicated that landslide densities increased 27 times on roads in the Macktush Creek watershed, 12 times in the Artlish River watershed, and 94 times in the Nahwitti River watershed (Guthrie 2002).

The study looked at the connectivity of all landslides to streams to determine whether there was a change in the relative impact on water resources. Similar to frequency increases in landslides themselves, 2–13 times more landslides hit streams (frequency rather than density) following logging over the three watersheds (Guthrie 2002).

The results indicate that, at least in the three watersheds examined on Vancouver Island, logging activities are substantially increasing landslide frequencies. Other frequency studies available for British Columbia (primarily the Queen Charlotte Islands and Clayoquot Sound) also cite considerable increases (O'Loughlin 1972; Rood 1984; Jakob 2000). However, the results vary considerably and cannot be uniformly applied across the Coast, let alone the province; while logging and road-building are probably causing increases elsewhere, the magnitude is unclear. The British Columbia Interior is particularly lacking in this information, with the exception of the terrain attribute studies that are in progress (Jordan 2002). Jordan (B.C. Min. For., pers. comm., 2001) has suggested that landslide densities appear to be about 10 times greater in the southeastern Interior following logging.

The ability to compare rates of landslides is critical for British Columbia professionals to effectively reduce the number and impacts of post-logging events. For example, terrain hazard maps are a widely used tool for geoscientists and geotechnical engineers in the forest industry in British Columbia. There is general agreement on qualitative definitions for moderate and high likelihood of landslides. The previous quantitative definitions (derived from studies in the Queen Charlotte Islands) of those hazards were acknowledged as inappropriate for provincial use and therefore removed. Unfortunately, beyond the qualitative definitions, practitioners are left to rely on intuition hampered by a fundamental lack of concrete knowledge about the changes in landslide frequencies following forestry activities. While management practices can reduce the rate of landslides without quantitative data, the ability to accurately gauge successes and learn from mistakes is certainly impaired without it. The discipline is left with no metric against which to measure its progress.

Road location and design in particular would benefit from landslide frequency and density data. Roads are arguably the major contributors to landslides, especially considering the relatively small area they comprise of a landscape, and yet they are the single features over which we have the most control. Preventative measures such as mapping high-hazard areas before an activity (i.e., road-building) takes place implies a goal of trying to reduce or eliminate landslides. The number of landslides caused by roads in this study seems to be sufficiently high as to question whether those goals are being met, and certainly to question the relative rates in other watersheds.

In British Columbia, the move towards risk mapping in the forest industry is probably inevitable. Risk mapping is several times more complicated than hazard mapping, and, even at its most qualitative, requires fundamental understanding of frequencies and probabilities. Understanding the actual impacts of logging activities on the natural rate of landslides becomes, therefore, even more fundamental.

CONCLUSIONS

Geoscientists and geotechnical engineers in the forest industry in British Columbia promote the importance of landslide mitigation and prevention. We have, as a professional group, an ongoing responsibility to reduce the potential damages caused by landslides and not to dismiss the notion as simply another mapping exercise. The watersheds examined in this study, while not necessarily representative of the province, show that forest harvesting and road-building resulted in many times more landslides than occurred naturally in the same watersheds (Guthrie 2002). We need to quantify this for much of the rest of the province as well.

Fortunately, the data are easily accessible. Air photograph interpretation is a basic part of most geoscience done in the forest industry in British Columbia, and minimal effort will produce frequency or density data for the interpreter. In addition, much can be gleaned from ongoing projects.

The challenge is predictable and two-fold. First, find out what our impact really is and use that information as a measurable baseline. Second, bring the landslide frequencies down. Legislation in British Columbia has probably made significant reductions to landslide frequency in places, but not without the conscientious application of expert skills. Geoscientists and geotechnical engineers need to continue to make strong recommendations designed to reduce the likelihood of landslides (rather than merely pointing to regulations). We should keep informed about the results of new studies and use the information in our own work. We should think creatively, trying to come up with or implement new solutions to landslide problems, and we should report on the results.

REFERENCES

Chapman, A. 2000. Slope and road hydrology in Clayoquot Sound. Report to the Science Council of British Columbia Chapman Geoscience Limited, Victoria, B.C.

Environment Canada. 1993. Canadian climate normals, 1961–1990, British Columbia. Atmos. Environ. Serv., Ottawa, Ont.

Gimbarzevsky, P. 1988. Mass wasting on the Queen Charlotte Islands—A regional inventory, British Columbia. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 29.

Guthrie, R.H. 1997. The characterization and dating of landslides in the Tsitika River and Schmidt Creek watersheds, Northern Vancouver Island, British Columbia. M.S. thesis. Univ. Victoria, Victoria, B.C.

———. 2002. The effects of logging on frequency and distribution of landslides in three watersheds on Vancouver Island, British Columbia. Geomorphology 43:275–94.

Hartman, G.F., J.C. Scrivener, and M.J. Miles. 1996. Impacts of logging in Carnation Creek, a high-energy coastal stream in British Columbia, and their implication for restoring fish habitat. Can. J. Fish. Aquat. Sci. 53:237–51.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. Geol. Surv. Can., B.C. Mem. 272.

Howes, D.E. 1987a. A terrain evaluation method for predicting terrain susceptible to post-logging landslide activity. B.C. Min. Environ. and Parks, Victoria, B.C. Tech. Rep. 28.

———. 1987b. A method for predicting terrain susceptible to landslides following forest-harvesting: A case study from the southern Coast Mountains, British Columbia. *In* Forest Hydrology and Watershed Management. Proc. International Assoc. Hydrological Sciences Symp., XIX General Assembly of the International Union of Geodesy and Geophysics, Aug. 19–22, Univ. British Columbia, Vancouver, B.C., 167:143–54.

Howes, D.E. and M. Sondheim. 1988. Quantitative definitions of stability classes as related to post-logging clearcut landslide occurrence: Part II. *In* Proc. 10th B.C. Soil Science Workshop. J.D. Lousier and G.W. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. 56, pp. 167–84.

Jakob, M. 2000. The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. Catena 38:279–300.

Jordan, P. 2002. Landslide frequencies and terrain attributes in Arrow and Kootenay Lake forest districts. *In* Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proc. P. Jordan and J. Orban (editors). Nelson, B.C., May 23–25, 2001. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

Millard, T. 1999. Debris flow initiation in coastal British Columbia gullies. B.C. Min. For., Vancouver Forest Region, Nanaimo, B.C. For. Res. Tech. Rep. TR-002.

Millard, T. and T. Rollerson. 2002. Terrain attribute studies—Vancouver Forest Region (abstract). *In* Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proc. P. Jordan and J. Orban (editors). Nelson, B.C., May 23–25, 2001. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

O'Loughlin, C.L. 1972. A preliminary study of landslides in the Coast Mountains of southwestern British Columbia. *In* Mountain Geomorphology, Geomorphological Processes in the Canadian Cordillera. H.O. Slaymaker and H.J. McPherson (editors). B.C. Geographical Ser. 14:101–11. Tantalus Research Limited, Vancouver, B.C.

Rollerson, T.P. 1992. Relationships between landscape attributes and landslide frequencies after logging: Skidegate Plateau, Queen Charlotte Islands. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 76.

Rollerson, T.P., C. Jones, K. Trainor, and B. Thomson. 1998. Linking post-logging landslides to terrain variables: Coast Mountains, British Columbia – preliminary analyses. *In* Proc. 8th International Congress of the International Assoc. for Engineering Geology and the Environment, Balkema, Rotterdam, Netherlands 3:1973–79.

Rood, K.M. 1984. An aerial photograph inventory of the frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 34.

Sauder, E.A., R.K. Krag, and G.V. Wellburn. 1987. Logging and mass wasting in the Pacific Northwest with application to the Queen Charlotte Islands, B.C. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 53.

Schuster, R.L. 1996. Socioeconomic significance of landslides. *In* Landslides: Investigation and mitigation. A.K. Turner and R.L. Schuster (editors). Transportation Res. Board, Natl. Acad. Sci., Washington, D.C. Spec. Rep. 247, pp. 12–35.

Schwab, J.W. 1983. Mass wasting: October-November 1978 storm, Rennell Sound, Queen Charlotte Islands, British Columbia. B.C. Min. For., Victoria, B.C. Res. Note 91.

———. 1998. Landslides on the Queen Charlotte Islands: Processes, rates and climatic events. *In* Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coast Research to Management Solutions. D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (editors). B.C. Min. For., Res. Program, Victoria, B.C., pp. 41–7.

Smith, R.B., P.R. Commandeur, and M.W. Ryan. 1986. Soils, vegetation, and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 41.

Thomson, B. 1987. Chapman Creek landslide inventory. 1:20 000 scale map with legend. B.C. Min. Environ., Lands and Parks, Victoria, B.C.

———. 1998. Terrain attribute study: Slope failure frequencies following logging in coastal British Columbia (abstract). *In* Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coast Research to Management Solutions. D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (editors). B.C. Min. For., Res. Program, Victoria, B.C., p. 271.

Yorath, C.J. and H.W. Nasmith. 1995. The geology of southern Vancouver Island, a field guide. Orca Book Publishers, Victoria, B.C.

Landslide Frequencies and Terrain Attributes in Arrow and Kootenay Lake Forest Districts

PETER JORDAN

ABSTRACT

Most studies of landslide frequencies and terrain attributes in British Columbia to date have been conducted in coastal regions, where landslide frequencies are high. The usual approach is to prepare a detailed terrain map of the study area, and do a statistical analysis that compares the attributes of landslide and non-landslide terrain polygons. In the Interior, this approach is impractical, as landslide frequencies are much lower than on the Coast, and it would be unaffordable to map a sufficiently large study area. In this study, we conducted a landslide inventory and terrain attribute study in Arrow and Kootenay Lake Forest Districts. Our approach was to conduct an air photo inventory of all landslides, natural and development-related, in forest land in the study area, which covers roughly 1 million ha. Within the project area, eight small map areas were selected, covering 13 870 ha and including 210 landslides. Detailed terrain maps were prepared for these areas, and almost all landslides were inspected in the field. For preliminary data analysis of the overall project area, a sub-area was selected, covering about one-quarter of the project area centred on the Slocan Valley. A set of random points was generated to provide a sample of non-landslide points. Using a geographic information system (GIS), several terrain and land use attributes were determined for each point, including bedrock geology, soil association, biogeoclimatic zone, land ownership, and grid-produced topographic attributes such as slope and aspect. A "hydrologic shadow" of forest development was defined, consisting of all roads and cutblocks, and areas downslope from them. Chi-squared Automatic Interaction Detection (CHAID) and logistic regression were used as analysis methods. Preliminary results of the analysis, as well as sampling and study design considerations, are discussed. An important question to be addressed by terrain attribute studies is whether the occurrence of development-related landslides is determined by terrain attributes that can be mapped, or whether it is largely independent of terrain factors and is instead determined by engineering factors such as road location and drainage control.

INTRODUCTION

In the Nelson Forest Region, landslides related to forest development are a significant issue, especially with respect to sediment introduced to streams used for community water supply, and potential risks from landslides and debris flows that reach populated valley bottoms. With the introduction of the Forest Practices Code in 1995, terrain stability mapping is being increasingly used as a planning tool in forestry to avoid and reduce landslide risk due to development. To investigate the causes of landslides in this region, and provide information to calibrate the terrain stability classification used in mapping, a landslide inventory and terrain attribute study in the Nelson Forest Region was conducted from 1996 to 2001. The objectives of the study were:

- to compile an inventory of landslides, both natural and development-related, in several study areas in the region;
- to examine the areal frequency of landslides;
- to investigate their causes; and
- to determine statistical relations between landslide frequency and terrain attributes.

Landslide inventories were compiled in three parts of the region, representing the range of geology, topography, and climate across the region. Most of the effort has gone into a study area covering a large part of Arrow and Kootenay Lake Forest Districts, which is the area that has had the greatest frequency of reported landslides related to forest development. The results from this study area are the subject of this paper.

Most studies of landslide frequencies and terrain attributes in British Columbia to date have been conducted in coastal regions, where landslide frequencies are high. The most common approach involves selecting a study area with a large number of landslides, preparing a detailed terrain map, and doing a statistical analysis that compares the attributes of landslide and non-landslide terrain polygons (Rollerson 1992). In the Interior, this approach is impractical, as landslide frequencies are much lower than on the Coast, and it would be unaffordable to map a sufficiently large study area. Our approach in this study was to conduct an air photo based inventory of landslides in a large study area, to field check the landslides, and to prepare terrain maps for small representative sub-areas.

Studies in coastal British Columbia have shown landslide frequencies of about 0.5 – 1.1 landslides per square kilometre per year (Ls/km^2/yr, where Ls = number of landslides) from clearcuts (not including roads) on western Vancouver Island and the Queen Charlotte Islands, respectively (Rollerson and Millard 1998), and 0.07 – 0.17 Ls/km^2/yr for three watersheds on Vancouver Island (Guthrie 2002). The highest reported landslide frequencies in British Columbia have been from the Queen Charlotte Islands. In a 200 km^2 study area on the west coast, Schwab (1988) reported an average failure rate in clearcuts of 10 Ls/km^2; 12% of the landslides were road-related.

Preliminary results from the Arrow and Kootenay Lake study area, previously reported in Jordan (2001), indicate that the frequency of development-related landslides in steep land areas (slopes greater than about 30%) is about 0.03 Ls/km^2/yr and the areal frequency of development-related landslides is about 10 times the natural landslide frequencies. An important difference between the results of studies in the British Columbia Interior and Coast is that the vast majority of development-related landslides in the Interior is caused by roads (about 90% as reported in Jordan 2001). On the Coast, some studies show that most landslides are caused by clearcuts (Schwab 1988), whereas others show that roads and harvesting are of about equal importance (Guthrie 2002).

APPROACH AND METHODOLOGY

At the beginning of the project, a study area was defined that included a large part of Arrow and Kootenay Lake Forest Districts, for the most part lying east of the Arrow Lakes and north of the Kootenay and Columbia Rivers. It includes a large part of the southern Selkirk Mountains and the western Purcell Mountains. This area was selected because it comprised most of the area of the two forest districts for which landslides related to forest development have been identified as an important management concern. This study area covers about 1.4 million ha, of which about 900 000 ha is provincial forest and private forest land (not including provincial parks, alpine areas, water bodies, agricultural land, etc.). The area is mountainous, with elevations ranging from about 500 m in the main valley bottoms, to mountain peaks at 2700–3000 m. The climate is humid; precipitation ranges from 600 to 1200 mm annually, which falls mostly as snow at higher elevations. The region is heavily forested; most of the land below treeline is covered with the commercially valuable forests of the Interior Cedar–Hemlock and the Engelmann Spruce–Subalpine Fir biogeoclimatic zones. Figure 1 shows the location of the study area.

Landslide Inventory

A systematic inventory of air photos was conducted for the study area, and all landslides visible on the air photos were located by eye from the air photos to 1:20 000 topographic maps (Terrain Resource Inventory Mapping, or TRIM maps). The inventory identified 1738 landslides. For each landslide, basic information that could be obtained from maps and air photos was recorded. This included size (as one of five size classes), slope position, slope steepness and aspect, type of landslide (e.g., debris slide, debris flow, slump), apparent cause, apparent age, spatial association with roads and cutblocks, and other information. The most recent systematic air photo coverage was used; the

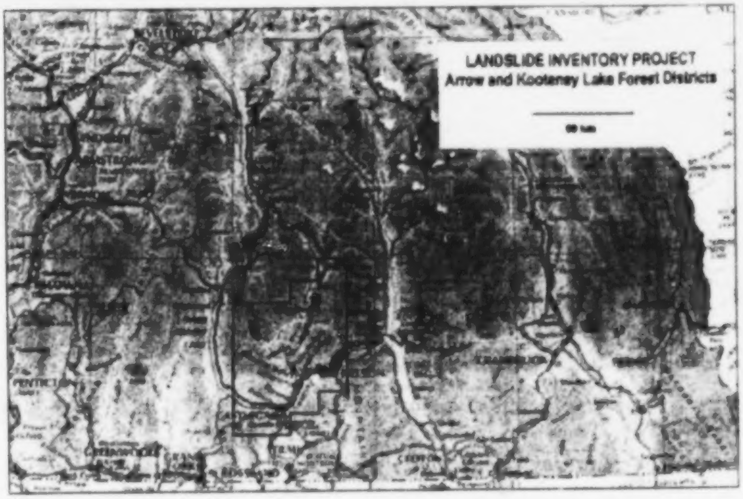
LANDSLIDE INVENTORY PROJECT
Arrow and Kootenay Lake Forest Districts

FIGURE 1 *Map of southeastern British Columbia, showing study areas. The original project area is outlined in green, and the southwest study area is outlined in black. The eight terrain map areas are shown in solid red.*

date of photography ranged from 1988 to 1997. In some cases, older air photos were also examined. More recent landslides were identified from records kept by the forest districts; since about 1990, forest companies have been required to report development-related landslides in their operating areas. The inventory is current up to the summer of 1999. The positions of the landslide initiation points were digitized from the maps to a geographic information system (GIS) using ArcView version 3.2. A satellite image taken in 1998, which is geo-referenced and can be used in a GIS, was used to confirm the position of many larger landslides.

Landslides were included in the inventory whether they were naturally occurring, or related to development of any kind. A lower limit of 0.02 ha was set for landslides to be included in the inventory. As explained below, this size limit may have been too small, because landslides of this size often cannot be reliably identified on air photos, and only landslides larger than 0.05 ha were included in the data analysis. For this inventory, a "landslide" was defined as a rapidly moving debris slide, debris flow, slump, or rockslide that had an identifiable starting point, and appeared to be either a first-time event, or a reoccurrence of a periodically failing landslide feature. This definition covers the types of slope failure commonly caused by forest development. Other types of slope failures, such as slow-moving slump-earthflows, bedrock slumps, chronic failures at the outside of river bends, chronic rockfall areas, etc., were not included. The distinction between slope failures to include or not include was often subjective, and is a source of error in the inventory of naturally occurring landslides. Another source of error was the subjectivity of deciding whether a complex feature with multiple initiation points should be entered as a single landslide or as several landslides.

A landslide inventory such as this has both spatial and temporal components. Although the date of most landslides is not known, it can be roughly estimated from the appearance on the air photo of successional vegetation on the landslide scar. Based on our experience, we estimate that most landslides are visible on air photos for about 30 years. This estimate is approximate; some very large landslides are visible for 50 years or more, while many small, shallow landslides revegetate quickly, and are difficult to recognize after 10 years. In this paper, the assumption is made that the landslide inventory represents a 30-year period. The term "landslide frequency" is used in this paper to describe both areal frequency (expressed as Ls/km^2) and temporal frequency ($Ls/km^2/yr$). Landslide frequency is also referred to as "landslide density"; temporal frequency is calculated from this using an assumed time span of 30 years.

Study Areas for Data Analysis

The design of the study is based on analysis of the data set at two scales:

1. analysis of the entire database, which is based on air photo interpretation for most landslides, using terrain attributes available in GIS but not including detailed terrain mapping; and
2. analysis of a small, higher-quality subset of the database, which is covered by detailed terrain mapping, and for which the landslides have been field-checked.

In this paper, preliminary data analyses are presented for two subsets of the overall project area, representing the above two scales. At this time, quality control and GIS data compilation for the remainder of the overall project area are still in progress.

The "southwest study area" covers about one-quarter of the project area centred on the Slocan Valley. This study area, consisting of 24 map sheets in the southwestern part of the project area, was selected to complete some data analysis more promptly to meet an immediate planning need, which was to obtain data on landslide frequency in the Slocan Valley portion of Arrow Forest District. For this purpose, a small area south of the Kootenay and Columbia Rivers, which was not part of the original project area, was added. This study area is shown in Figure 2.

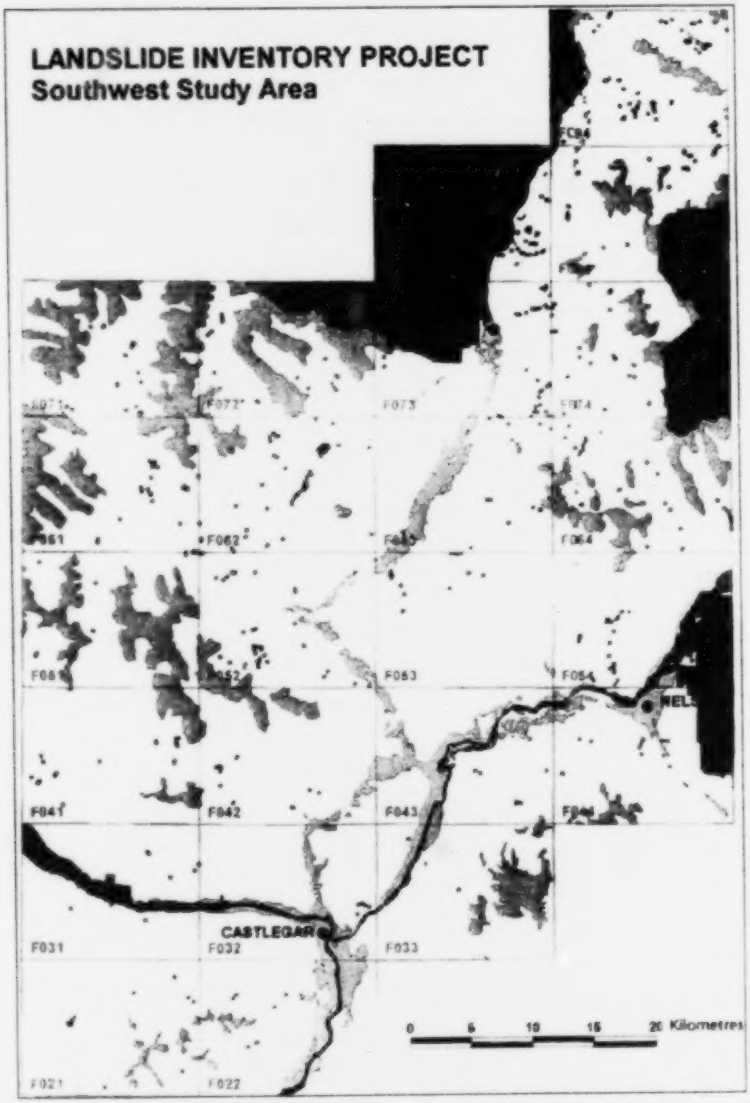
LANDSLIDE INVENTORY PROJECT
Southwest Study Area
F072
F073
F074
F061
F062
F063
F064
F053
F054
F041
F042
F043
F031
F032
F033
F021
F022
CASTLEGAR
0
5
10
15
20 Kilometres

FIGURE 2 *Southwest (Slocan Valley) study area. Landslides are red dots. Non-forest areas are lakes (dark blue), parks (green), alpine (light blue), and urban/agricultural (yellow). Note: If viewed as a black-and-white image, these areas range in order from darkest to lightest grey.*

The "terrain map study area" comprises eight small map areas, covering 13 870 ha and including 210 landslides. Detailed terrain maps were prepared for these areas, and almost all landslides were inspected in the field. This produced a smaller but higher-quality database, which included additional data based on field observations, such as field-measured slope, drainage class, and surficial material. The eight map areas are shown in Figure 1.

STATISTICAL METHODS

For the terrain map study area, two approaches were used for preparing data sets for statistical analysis. One uses the terrain map polygons, and various attributes assigned to each polygon. The variable of interest is the density, or areal frequency, of landslides in each polygon (Ls/km^2). The attributes of polygons with one or more landslides per polygon can be compared with those polygons with no landslides. This is the approach used in most studies in coastal British Columbia (Rollerson and Millard 1998; Rollerson et al. 2001), and it is well suited to analyzing polygon-based data of the type collected by field-based terrain mapping. The second approach is to generate a set of random points covering the study area. This produces a random sample of non-landslide points, which can be statistically compared with the landslide points. This method is best suited for areas that have no uniform coverage by terrain maps, but have data available in GIS from a variety of sources. For the southwest study area, only the random point approach was used. Further detail on the methods used in the two approaches is given below.

For statistical analysis, three methods are used:

- The primary statistical tool is CHAID (Chi-squared Automatic Interaction Detection). This method (SPSS Inc. 1997) identifies the most significant variables, and computes landslide density for different combinations of variables.
- Logistic regression (Bergerud 1996) is another statistical tool that we are investigating as an alternative method of identifying significant variables.
- Univariate analysis is used to present a simple summary of the effect of the most significant variables on landslide density.

These methods are used to identify the terrain attributes that have a significant influence of landslide density; to compute the natural and development-related landslide density for different combinations of variables; and to examine the relative importance of terrain attributes and forest development on landslide density.

The variables used for analysis, and their values, are shown in Table 1.

CHAID Analysis

The application of CHAID analysis to landslide data sets has been described in several studies in the Vancouver Forest Region (Rollerson et al. 2001). For this study, the analysis is similar, except that it is based on points (landslide and random non-landslide points) instead of terrain polygons. The landslide points represent the total population of identified landslides in the study area. The non-landslide points are a random sample. The area represented by each non-landslide point can be readily calculated. Landslide points are assumed

TABLE 1 *Categorical variables used for CHAID and logistic regression analysis, and abbreviations of values.*

Variable	Values for CHAID		Values for logistic regression	
Slope class	1	< 20°	GSLOPE	
	2	20–25°	(continuous variable)	
	3	25–30°		
	4	30–35°		
	5	35–40°		
	6	> 40°		
Soil category (for soil and landform maps)	K	kame	Soil_R	
	G	glaciofluvial	1	all others
	M1	morainal (ablation till)	2	M2
	M2	morainal (basal till)	3	K, G
	C1	shallow colluvium over rock		
	C2	deep colluvium		
	F	fluvial		
	R	rock		
Terrain category (for terrain maps)	K	kame	Tcat_R	
	G	glaciofluvial	1	all others
	M1	shallow morainal	2	M2
	M2	deep morainal	3	K, G
	C	colluvium		
	F	fluvial		
	R	rock		
Drainage class	r	rapid	Drain_R	
	w	well	1	r
	m	moderately well	2	w
	i	imperfect	3	m, i, p
	p	poor		
Geology	g	granitic	Geol_R (southwest)	
	gn	gneiss	1	fs
	fs	fine sedimentary	2	g
	cs	coarse sedimentary	3	all others
	ms	metasedimentary	Geol_R (terrain map)	
	ps	Precambrian sedimentary	1	ms
	v	volcanic	2	g
	Q	Quaternary	3	all others
Gullies	freq.	frequent (many)	Gully_R	
	infreq.	infrequent (few)	0	none
	single		1	any gullies
	none			
Climate	dry	IDF	Climate_R	
	moist	MS, ICH moist, ESSFdc, dk	1	moist, dry
	wet	ICHwk, ESSF moist	2	wet, very wet
	very wet	ICHvk, ESSFvc		
Texture			TexC	
			Sandy	S, LS
			Loamy	SL, L
			Silty	SiL

to not contribute to this area. In fact, they do represent a small area. Random points were rejected if they fell within a 50-m radius of a landslide. If each landslide point represents this area (0.79 ha), then neglecting the area of the landslides introduces an error of only 0.15% in the calculated area per non-landslide point.

To run a CHAID analysis, the dependent or response variable (landslide point yes/no or 1/0) and several independent or input variables are selected. Input and response variable can be categorical or continuous; however, only categorical variables were used. The model determines which input variable is the most significant, and tabulates the number of landslide and non-landslide points in each category. At the second level, within each category, it determines the next most significant variable, and so on for each successive level. The user can select the significance level, the maximum number of branches, and the minimum number of points permitted for parent and child nodes. Categories within a variable are combined if they are not significantly different, or if the number of points in a child node would be smaller than the specified minimum. A node is not split further if there are no significant variables or if it is smaller than the number of points specified for a parent node. An important limitation of the method is that the sample size gets smaller with each split, so the results of some branches can be of dubious value if the number of points in a node is small.

CHAID analysis can involve considerable trial and error, as well as subjectivity, with different subsets of the database, different combinations of input variables, and different categories within a variable, as well as various splitting rules, being chosen. When several variables are of similar significance, results can be inconsistent depending on the combination of variables and rules chosen. In the preliminary results reported below, only a few examples of the many CHAID runs possible are included.

Logistic Regression

Logistic regression was also tested as an analysis tool. The method and its application to biometrics is described by Bergerud (1996), and Roberts (2001) experimented with its use in analyzing landslide and terrain attribute data. It fits a linear model to the data, and, unlike CHAID, all the data are used in fitting the model. This should be an important advantage; however, logistic regression has a disadvantage, which is that it becomes unstable if the number of categories in the input variables is too large. The response variable must be binomial (yes/no or 1/0). Input variables can be continuous or categorical, and categorical variables work best if they are binomial. The output consists of a model that can be used to predict the probability of landslides for a given combination of input variables; however, it is awkward to apply, and does not give the easily interpreted graphical results that CHAID does.

For this preliminary analysis, logistic regression was used only to test the relative significance of input variables, not to develop a predictive model. The logistic regression routine in the JMP statistics package (SAS Institute Inc. 1995) was used.

Measurement of Slope Gradient

An important variable, which all studies of landslide occurrence and frequency have identified as significant, is slope. For areas not covered by field checking or terrain mapping, slope must be obtained from topographic mapping; the best map coverage over the whole project area is the TRIM maps and database. These are available in two forms: contour maps, from which an analog measurement of slope can be made for any point; and a digital elevation model (DEM), from which a grid of slope and aspect can be derived. The DEM contains all the points that were used to derive the contours. The British Columbia government has published a 25-m grid of elevation points derived from the TRIM DEM. This grid was used for the analysis reported here. ArcView version 3.2 and its Spatial Analyst extension (ESRI Inc. 1996) were used for analysis of slope and other GIS data.

For each landslide in the inventory, the slope in percent was estimated manually from the contour map by using a template (a plastic transparency on which the contour spacing was marked for a range of slopes in 5% increments). This procedure is subject to operator error, and although it probably gives accurate results for long, uniform slopes, it is limited by the resolution of the contour maps in areas of complex topography.

If the manually measured slopes are compared with the TRIM grid slopes, there is a great deal of scatter (Figure 3). Also, it is possible to compute a grid and a derived set of slopes using algorithms different from the published TRIM grid. Such a grid has been prepared by Bob Pack of Utah State University (R.T. Pack, Utah State Univ., pers. comm., 2001). A sample of it is shown in Figure 4, which compares slopes of the two grids for a small sample area. Although on average they are similar, they differ for specific locations.

There are several reasons for the errors in the grid and manual slopes:

- Some of the slopes taken manually from contour maps are in error. Sometimes, the landslide position was only approximate when first located, and was shifted later in GIS using the geo-referenced satellite photo. Also, sometimes data for a cluster of similar landslides were recorded together, with a single average slope assigned to all.
- Slopes of a grid-based DEM are inherently less precise than those calculated from a TIN ("triangular irregular network") using all the original TRIM DEM points.
- In complex terrain, calculated grid slopes vary greatly amongst adjacent pixels. If a landslide initiation point happens to occur close to a pixel boundary, it is arbitrary to which pixel it is assigned (see Figure 4b for an example).

Although it is not possible to readily analyze these sources of error on qualitatively inspecting the data, we decided that these errors were random in

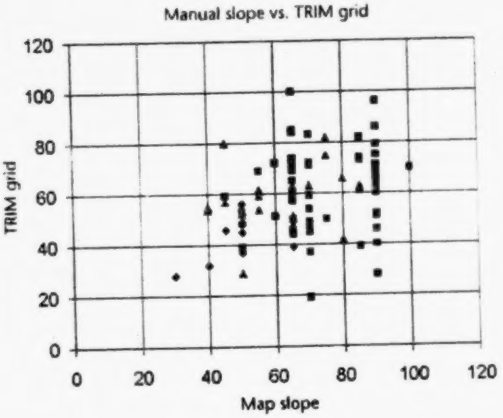

FIGURE 3 *Comparison of map slopes and grid slopes for three sample map sheets. Manual slope = Map slope = slope taken manually from contour map during inventory. TRIM Grid = grid cell slope from 25-m TRIM DEM grid. Slopes are in percent. The scatter is probably due both to random error associated with assigning points to a grid cell, and to errors in manually estimating slope from the contour map. Landslide points are from map sheets 82F.041 (black diamonds), 82F.094 (red squares), and 82K.063 (green triangles).*

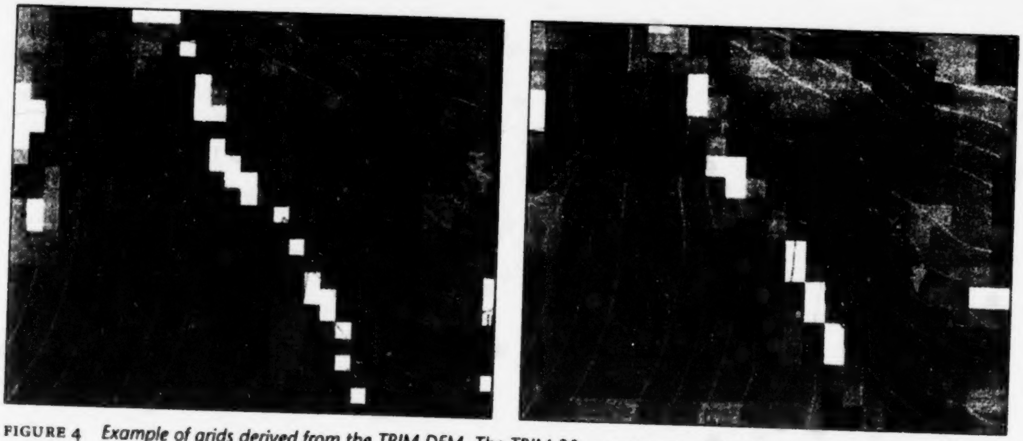

FIGURE 4 *Example of grids derived from the TRIM DEM. The TRIM 20-m contours are also shown. A (left). 20-m grid computed by R.T. Pack, using a different algorithm than the TRIM grid. B (right). 25-m TRIM grid for the same area.*

In both figures, slope ranges are (from lightest to darkest tone): < 20°; 20–25°; 25–30°; 30–35°; 35–40°; and > 40°.

The example is from map sheet 82K.063 (Ferguson map area), and shows a sample landslide point. Slope data for this point are: from Pack grid – 41°; from TRIM grid – 33°; manual slope (from inventory database) – 80% (39°); slope calculated from distance between contours – 38°; slope measured in the field – 80% (39°).

Note that on the TRIM grid, the landslide point happens to fall almost exactly on the boundary between two grid cells. A position only 1 m farther west would have given a different slope. For some hypothetical points (e.g., Figure 4B, below the landslide point), it would be possible to assign the lowest or the highest slope class. This example is not meant to imply lower accuracy of the TRIM grid, but to illustrate the random errors in assigning grid cell slopes to points.

nature, not systematic. As long as the grid slopes are not biased, the random error of individual grid points will not limit the statistical analysis, if the sample size is sufficiently large.

Other GIS Data

To statistically investigate the role of forest development on landslide frequency, information is needed in GIS form on the location of roads and cutblocks. This information is difficult to obtain in a usable format from the forest inventory database. Another relevant point is that our results to date show that many landslides occur below roads and cutblocks, not on them, due to drainage diversions and other hydrologic effects such as increased runoff (Jordan 2001). Therefore, we used a different approach for the southwest study area. This was to identify "development polygons," which are defined as roads and cutblocks and all areas downslope from them (Figures 5 and 6). In effect, these outline the "hydrologic shadow" of forest development. Development polygons were obtained by printing an overlay of contours and streams onto the satellite photo that covers Arrow Forest District. The polygon boundaries were identified from the satellite image and contours, drawn manually on the map, and then digitized. As this work is labour-intensive, we did it only for this smaller study area, not for the entire project area.

Another datum that became available in digital form during the past few years is the 1:50 000 soil and landform maps, published in about 1980 by the former Resource Analysis Branch of the British Columbia government. These maps have been digitized and made available in Arc format on the Internet site of the Ministry of Energy and Mines. Although the mapping is less detailed and of lower reliability than more recent 1:20 000 terrain mapping, it is useful in that it provides information on the general distribution of major

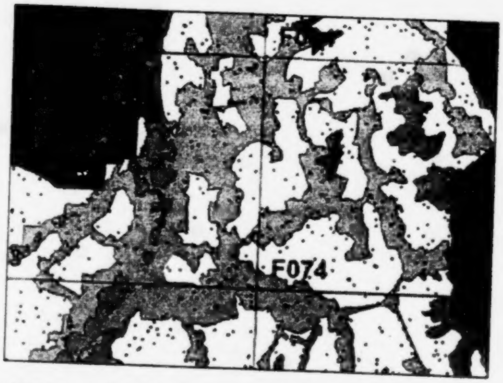

FIGURE 5 *Part of southwest study area; Slocan Lake in upper left. Development polygons are shown in grey-green. Landslides are red dots, and random points are small black dots.*

FIGURE 6 *Satellite photo covering same area as Figure 5.*

terrain types such as glaciofluvial, morainal, and exposed rock. Bedrock geology compilation maps at 1:250 000 scale are also available from this source, and in the last year we converted those to a form that is useful for this study.

RESULTS FOR SOUTHWEST STUDY AREA

The analysis for the southwest study area was done using the database obtained from air photo interpretation, and terrain attributes available from GIS data. The random grid approach was used to compare the attributes of landslide and non-landslide points.

A preliminary statistical analysis was done on the data available so far. This was done primarily using CHAID, and the use of logistic regression was also explored. Analysis was done on the net forested area. This is the study area, minus provincial parks and non-forest areas such as lakes, alpine, and agricultural land. A set of random points was generated covering the study area, of which 5652 points fell in the net forested area. The analysis compares the attributes of the landslide points with the random set of non-landslide points. There are a total of 579 landslide points in the study area. Of these, only the 433 landslides that are of size class 2 or larger (> 0.05 ha) were used for analysis. This size limit was chosen because our experience in field checking has shown that landslides smaller than this cannot be reliably identified on air photos, and because previous studies in the Vancouver Forest Region have used this size limit.

For each landslide and random non-landslide point, the attributes to be tested were obtained from GIS files. These included soil category from the soil and landform maps, development polygons, land ownership, climate category from biogeoclimatic maps, and bedrock geology category. Slope and aspect were obtained from the TRIM 25-m DEM grid.

An example of a chaid output tree is shown in Figure 7. Only one output tree is shown, as the trees can be very large. Instead, output is summarized here as simplified tables (Tables 2a and 2b), which give the results as landslide density in landslides per square kilometre. For simplicity, results are given only for the first two levels.

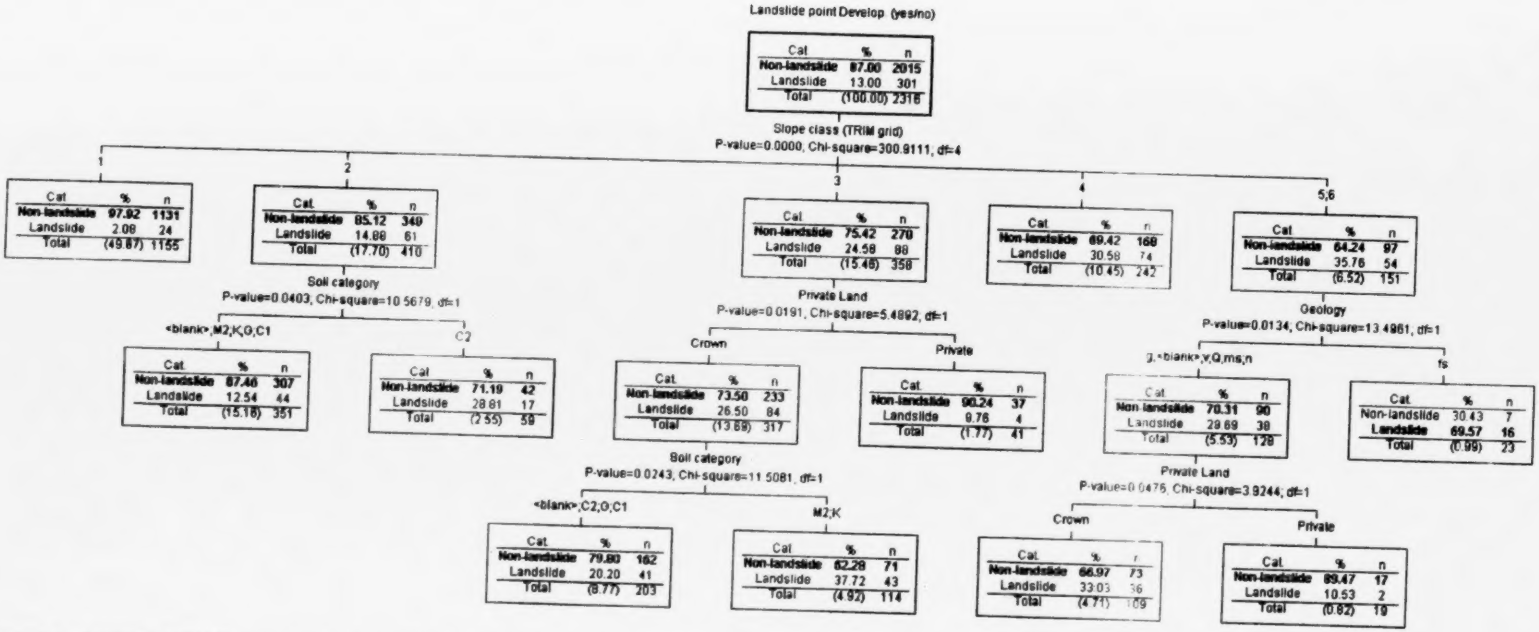
Landslide point Develop (yes/no)
Cat % n
Non-landslide 87.00 2015
Landslide 13.00 301
Total (100.00) 2316
Slope class (TRIM grid)
P-value=0.0000; Chi-square=300.9111; df=4
1
Cat % n
Non-landslide 97.92 1131
Landslide 2.08 24
Total (49.87) 1155
2
Cat % n
Non-landslide 85.12 349
Landslide 14.88 61
Total (17.70) 410
Soil category
P-value=0.0403; Chi-square=10.5679; df=1
<blank>;M2;K;O;C1
Cat % n
Non-landslide 87.46 307
Landslide 12.54 44
Total (15.16) 351
C2
Cat % n
Non-landslide 71.19 42
Landslide 28.81 17
Total (2.55) 59
3
Cat % n
Non-landslide 75.42 270
Landslide 24.58 88
Total (15.46) 358
Private Land
P-value=0.0191; Chi-square=5.4892; df=1
Crown
Cat % n
Non-landslide 73.50 233
Landslide 26.50 84
Total (13.69) 317
Soil category
P-value=0.0243; Chi-square=11.5081; df=1
<blank>;C2;O;C1
Cat % n
Non-landslide 79.80 162
Landslide 20.20 41
Total (8.77) 203
M2;K
Cat % n
Non-landslide 62.28 71
Landslide 37.72 43
Total (4.92) 114
Private
Cat % n
Non-landslide 90.24 37
Landslide 9.76 4
Total (1.77) 41
4
Cat % n
Non-landslide 69.42 168
Landslide 30.58 74
Total (10.45) 242
5;6
Cat % n
Non-landslide 64.24 97
Landslide 35.76 54
Total (6.52) 151
Geology
P-value=0.0134; Chi-square=13.4961; df=1
g;<blank>;v;Q;ms;n
Cat % n
Non-landslide 70.31 90
Landslide 29.69 38
Total (5.53) 128
Private Land
P-value=0.0476; Chi-square=3.9244; df=1
Crown
Cat % n
Non-landslide 66.97 73
Landslide 33.03 36
Total (4.71) 109
Private
Cat % n
Non-landslide 89.47 17
Landslide 10.53 2
Total (0.82) 19
fs
Cat % n
Non-landslide 30.43 7
Landslide 69.57 16
Total (0.99) 23

FIGURE 7 *Example of CHAID output: southwest data set, development polygons, and development-related landslides. This CHAID tree corresponds to Table 2b.*

TABLE 2a *CHAID summary for southwest data set: all points. Total area = 298 344 ha; each random point represents 52.79 ha.*

Level*	Variable	Value	No. of random points	No. of landslides	Landslide density (Ls/km^2)
Whole area			**5652**	**433**	**0.145**
1	**Development polygon**	**In**	**2015**	**342**	**0.32**
2	**Slope class**	**5,6**	97	66	1.29
2	**Slope class**	**4**	168	90	1.02
2	**Slope class**	**3**	270	92	0.65
2	**Slope class**	**2**	349	63	0.34
2	**Slope class**	1	1131	31	0.05
1	**Development polygon**	**Out**	**3637**	**91**	**0.05**
2	**Soil category**	K	219	17	0.15
2	**Soil category**	M2	466	15	0.06
2	**Soil category**	M1,C1,C2,G,F,R	2906	48	0.03
2	**Soil category**	missing	46	11	0.45

* 3rd and 4th levels: geology, private land, slope class, aspect.

TABLE 2b *CHAID summary for southwest data set: development polygons, development-related landslides only. Area = 109 581 ha; each random point represents 54.38 ha.*

Level*	Variable	Value	No. of random points	No. of landslides	Landslide density (Ls/km^2)
Whole area			2015	301	0.275
1	**Slope class**	5,6	97	54	1.02
2	Geology	fs	7	16	4.20
2	Geology	all other	90	38	0.78
1	Slope class	4	168	74	0.81
1	**Slope class**	**3**	**270**	**88**	**0.60**
2	Private land	Crown	233	84	0.66
2	Private land	private	37	4	0.20
1	**Slope class**	**2**	**349**	**61**	**0.32**
2	Soil category	C2	42	17	0.74
2	Soil category	all other	307	44	0.26
1	**Slope class**	1	**1131**	**24**	**0.04**

* 3rd and 4th levels: private land, soil category, geology.

Table 2a shows the first analysis, on all landslides > 0.05 ha. The variable "inside/outside of a development polygon" was by far the most significant, with landslide densities of 0.32 and 0.05 Ls/km^2, respectively. This result implies that the presence of a road or cutblock upslope increases the probability of a landslide by over 6 times (ignoring the role of other attributes), and that the presence or absence of development is more important than terrain attributes.

Further analysis was done using a subset of the data consisting of landslides > 0.05 ha, which are in development polygons and were identified as development-related. This removes the overwhelming influence of the "inside/outside of a development polygon" variable, and enables the significance of the other attributes to be compared. The results of this analysis are shown in Table 2b and Figure 7. Slope class was the most significant input variable, with geology, soil category, and private land being significant at the second level.

For the application of logistic regression, slope was input as a continuous variable, and the number of categories of the other variables was reduced in most cases to two or three, by referring to the chaid trees to combine similar categories. Table 3 shows the results for the same data set as Table 2b. Slope is by far the most significant variable, and geology and land ownership are the next most significant. Soil category was not significant at the 0.05 level, which contradicts the chaid results (although with chaid it was significant only for one of six slope classes). Note that the abbreviations used for the output in Tables 2–5 are given in Table 1.

It is useful to examine the effects of the input variables singly, in graphical form. This is done in Figures 8 and 9, for slope class and geology. In each graph, the left (grey) bars are a histogram of areal coverage, and the right (coloured) bars are the landslide density for each category. The data are for development-related landslides in development polygons. Some comments on the effects of individual variables follow.

Slope As would be expected, landslide frequency increases with increasing slope, peaking in the 35–40° class. Slopes steeper than 40° may be less subject to landslides because they are often bare bedrock with little surficial material to slide. Also, there is very little forest development on such steep slopes (although landslides on these slopes can be caused by drainage diversions from development upslope).

TABLE 3 *Logistic regression output, southwest data set by random points. Development-related landslides and development polygons only.*

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSq
GSLOPE	1	1	197.97727	0.0000
Private	2	1	14.31294	0.0002
Soil_R	3	2	2.63985	0.2672
Climat_R	2	1	5.82146	0.0158
Geol_R	3	2	15.02341	0.0005

Notes: Nparm = number of parameters (for categorical variables); GSLOPE = grid slope as continuous variable; Private = private or Crown land; Soil_R = soil category; Climat_R = climate category; Geol_R = geology category; _R indicates categories have been simplified for regression analysis.

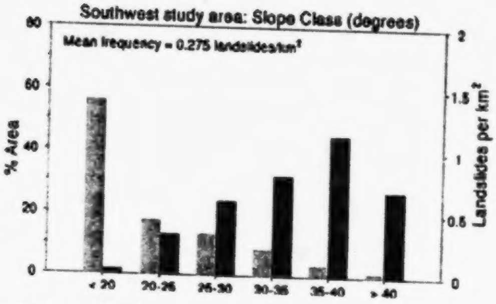

FIGURE 8 *Southwest data set, development polygons, and development-related landslides. Landslide density by slope class. Left bars (grey) are areal distribution; right bars (coloured) are landslide density.*

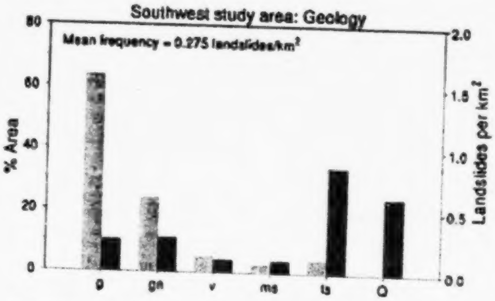

FIGURE 9 *Southwest data set, development-related landslides. Landslide density by geology category. Categories are granite, gneiss, volcanic, metasedimentary, fine sedimentary, Quaternary.*

Geology

Bedrock geology is a significant variable only in the steepest slope classes (Table 2b). The high landslide density for "fine sedimentary" may be misleading. These rocks are confined to a small area around Silverton and Sandon, which has had extensive mining development for 120 years, and which also consists of very steep terrain. Old mine roads and mine workings are widespread. The frequent landslides may be due to this development, not to any properties of the bedrock itself. The relatively high landslide density in granitic rocks (also evident in Figure 15) may reflect road fill failures in uncohesive granitic soils.

Soil Category

In the CHAID analysis, soil category was a secondary factor for landslide outside of development polygons, and for gentler slopes. In the logistic regression analysis, it was not a significant variable. There is a tendency for kame to have the highest landslide density, followed by deep morainal (Table 2a; consistent with terrain categories in Figure 14). The low statistical significance of soil category is surprising, as it contradicts the results from the terrain map study area. It may be that the 1:50 000 soils maps are not sufficiently accurate to properly represent the terrain types.

Land Ownership

The analysis showed a higher incidence of landslides on Crown compared with private land. This result was surprising, as casual observation suggests that landslides in areas of private land logging are frequent, and are caused by the low standards of road construction and logging practices that are prevalent on private land. Casual observation may be misleading, as many of the private land landslides are in high-visibility locations close to highways and populated areas.

Climate, Elevation, and Aspect

Climate was a marginally significant variable in logistic regression, and also in the lower levels of some CHAID runs. The moist climate zone had a higher landslide density than dry, wet, or very wet; however, there is no apparent physical reason for this. The moist zone occupies three-quarters of the study area. Similarly, there was some tendency for the middle elevation zones to have a higher landslide density. This may be simply because that is where most of the forest development activity is. Climate is derived from the biogeoclimatic zones, which are correlated with elevation. Aspect showed up on some CHAID runs, with a tendency for north to northwest aspects to have a slightly higher landslide density. Again, there is no apparent physical reason for this finding.

RESULTS FOR TERRAIN MAP STUDY AREA

The eight map areas in the terrain map data set cover 13 870 ha (1.5% of the 900 000 ha of forest land in the overall study area), and include 210 landslides (12% of the landslides in the total area). The map areas were chosen to comprise areas of high landslide density, in order that an area that could be terrain mapped affordably would contain enough landslides for statistical analysis. The map areas have steeper terrain than average, and have extensive forest development. They were selected to have a wide geographic distribution, and to represent the main geologic categories and climate zones present in the overall area.

For statistical analysis, the GIS and database files were merged to treat the eight map areas as a single data set. This data set can be analyzed in the same way as data sets for the coastal regions of the province, on the basis of terrain polygons. Although the data set is deliberately biased towards areas of high landslide density, it should be unbiased with respect to terrain and other factors affecting landslide probability, as long as it is representative of the range of these factors in the overall project area. The purpose of this analysis is not to determine landslide densities, which are known to be higher than average, but to examine the terrain attributes that may have a significant influence on landslide probability.

This data set is of higher quality than the data set for the overall project area, and the southwest subset described in the previous section. The landslides have been identified from fieldwork as well as air photos, and most landslides have been field checked. Landslide positions were obtained by monorestitution from the air photos, as were terrain polygon boundaries.

Two types of CHAID analysis were done: one based on the terrain polygons and one using random points. Figures 10 and 11 show one of the eight map areas as an example. Figure 11 shows the terrain polygons and terrain categories, and the random points. Note that some small polygons are missed by the random points. Slope classes from the TRIM DEM grid were used for the random point analysis but not the polygon analysis.

For statistical analysis, the terrain label for each polygon was reduced to one of eight terrain categories. These are listed in Table 1. The category describes the dominant terrain type in each polygon, but does not consider minor terrain types that might be present. When doing the mapping, areas that were consistently < 20° in slope were not mapped. These are shown as blank polygons (Figure 11) and are not included in the analysis.

The analysis reported here uses a subset of the data that includes the development-related landslides, and only the mapped polygons (i.e., the unmapped, low-slope polygons are not included).

For the polygon CHAID analysis, polygon areas were weighted by a factor that is numerically equal to the area to the nearest hectare. This creates a large number of pseudo-polygons, or replicates (Table 4a). The response variable was the landslide density for each polygon. Input variables included average polygon slope (as a slope class), terrain category, soil texture, drainage class, and presence of gullies. All these data were taken from the terrain mapping database and are based on fieldwork. In addition, two variables that indicate the presence of development were used: "logging in polygon" and "road in polygon." The mapper recorded these during terrain mapping. They are binomial variables, which do not indicate how much development there is, or where the road or logging is, in relation to a landslide. At present, no digital files are available for roads and cutblocks, although these may be added to the data set in the future, along with development polygons as previously described. Geology and climate categories were also used as variables.

For the CHAID analysis using random points, the TRIM grid slope was used for each landslide and non-landslide point instead of the polygon average slope. Other variables attached to polygons, such as terrain category, drainage class, and gullies, were taken from the polygon in which each point falls. The "logging in polygon" and "road in polygon" variables were not used.

Tables 4a and 4b summarize the CHAID results for polygon and random point data, respectively. It is surprising that the two methods give different results. Gullies and terrain category are the most significant for the polygon

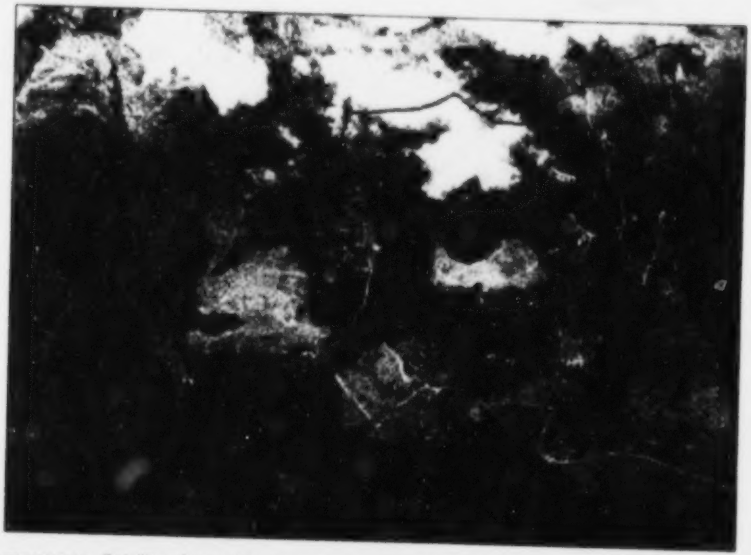

FIGURE 10 *Satellite photo of Ferguson map area, with landslides shown as red points. Note the two large landslides in lower centre.*

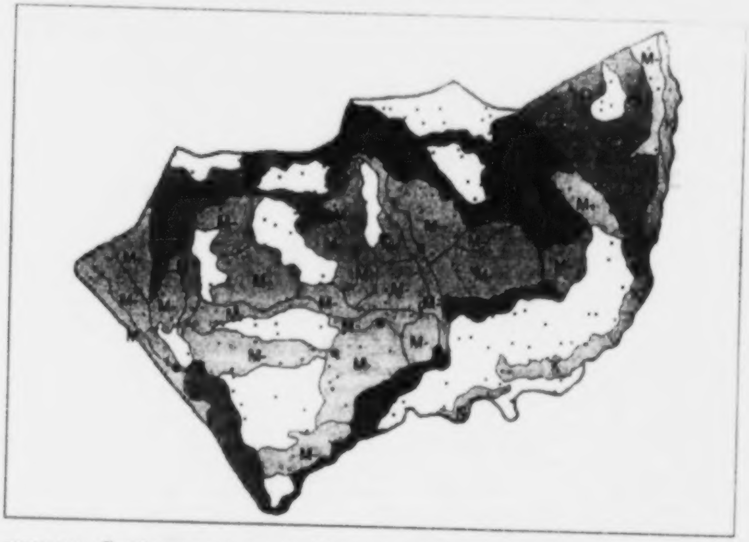

FIGURE 11 *Terrain map polygons. In this figure, the full terrain map symbols are replaced by the simple terrain categories: R = rock; C- = shallow colluvium; M- = shallow morainal; M+ = deep morainal; K = kame (morainal-glaciofluvial complex). White areas are unmapped polygons gentler than 20°. Red dots are landslides, and the random points are shown as black dots.*

and point runs, respectively, but each is of relatively low significance in the other run. The low significance of slope is also unexpected. Also, in experimenting with the CHAID runs, differences in the variables selected for each run sometimes produced different results in the significance of other variables. This may indicate that several variables are of similar significance levels, or are highly intercorrelated.

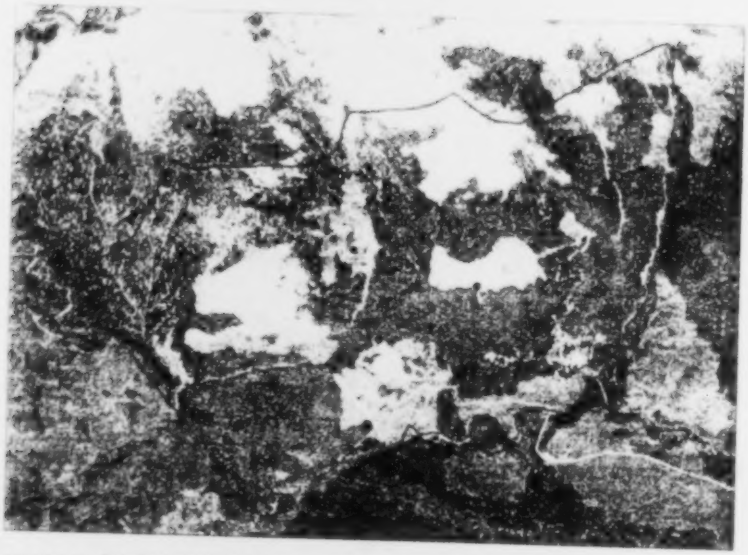

FIGURE 10 *Satellite photo of Ferguson map area, with landslides shown as red points. Note the two large landslides in lower center.*

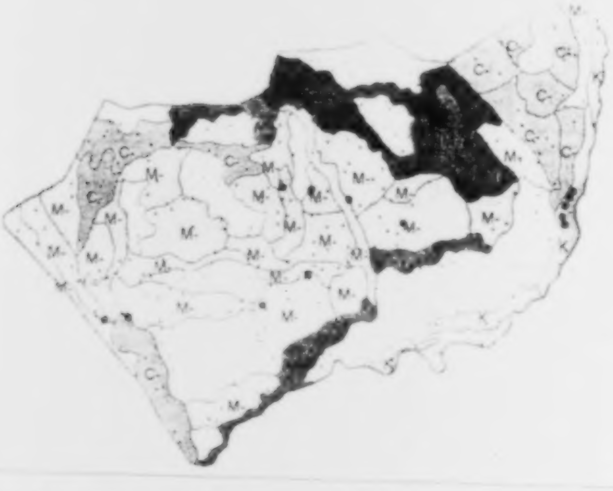

FIGURE 11 *Terrain map polygons. In this figure the full terrain map symbols are replaced by the simple terrain categories: R is rock; C- is shallow colluvium; M- is shallow morainal; M= is deep morainal; K is kame (morainal glaciofluvial complex). White areas are unmapped polygons gentler than 25°. Red dots are landslides, and the random points are shown in black dots.*

and profile curv, respectively, and [illegible] other run. The low significance of [illegible]. Also, in every iteration with the [illegible] ratio, differences in the variables selected for each run sometimes produced different results in the significance of other variables. This may indicate that several variables are of similar significance levels or are highly intercorrelated.

TABLE 4a *CHAID summary for terrain map areas, polygon data. Total area 13 870 ha; 210 landslides; 163 development-related landslide; 620 mapped polygons.*

Level*	Variable	Value	N (polygons weighted by area)	Landslide density (Ls/km^2)
Whole area			11 183	1.399
1	**Gullies**	**freq, infreq**	5 365	2.04
2	Road in polygon	yes	2 927	3.13
2	Road in polygon	no	2 438	0.73
1	**Gullies**	**single**	1 102	1.57
2	Road in polygon	yes	698	2.48
2	Road in polygon	no	404	0
1	**Gullies**	**none**	4 716	0.63
2	Slope class	5,6	714	2.58
2	Slope class	3,4	2 688	0.39
2	Slope class	2	676	0
2	Slope class	1	638	0.17

* 3rd and 4th levels: terrain category, logging in polygon.

TABLE 4b *CHAID summary for terrain map areas, random points. Number of random points in total area = 3547; each point represents 3.91 ha. Analysis includes mapped polygons and development-related landslides only.*

Level*	Variable	Value	No. random points	No. of landslides	Landslide density (Ls/km^2)
Whole area			2825	163	1.476
1	**Terrain category**	**K, G**	**204**	**49**	**6.14**
2	Drainage class	m	4	9	57.5
2	Drainage class	r	16	9	14.39
2	Drainage class	w	156	31	5.08
2	Drainage class	i, missing	28	0	0
1	**Terrain category**	**M2**	**460**	**37**	**2.06**
1	**Terrain category**	**M1**	**862**	**37**	**1.10**
2	Gullies	freq, infreq, single	398	36	2.31
2	Gullies	none	464	1	0.06
1	**Terrain category**	**C**	**1015**	**37**	**0.93**
2	Geology	ms	229	23	2.57
2	Geology	all others	786	14	0.46
1	**Terrain category**	**F, R**	**284**	**3**	**0.27**

* 3rd and 4th levels: geology, gullies, climate, slope class.

Table 5 shows the results for logistic regression, using the random point data set. Logistic regression cannot be done for the polygon data except in a simplified form, using just the presence or absence of landslides rather than landslide density, as the response variable must be binomial. The results are in general agreement with the CHAID run for random points; terrain category is the most significant variable, geology and gullies are next, followed by slope and drainage class. Climate and texture were not significant at the 95% level.

Figures 12–15 show some results for single variables, as histograms of landslide density. They are based on the random point data set, and use only the development-related landslides and points within the mapped polygons, as in the CHAID and logistic regression runs. Some comments on individual variables follow.

TABLE 5 *Logistic regression output, terrain map areas by random points. Development-related landslides, mapped polygons only.*

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSq
GSLOPE	1	1	14.501782	0.0001
Climat_R	2	1	2.318856	0.1278
Geol_R	3	2	23.292554	0.0000
Tcat_R	3	2	80.410226	0.0000
TexC	4	3	3.342317	0.3418
Drain_R	3	2	8.806342	0.0122
Gully_R	2	1	21.827448	0.0000

Notes: Nparm = number of parameters (for categorical variables); GSLOPE = grid slope as continuous variable; Climat_R = climate category; Geol_R = geology category; Tcat_R = terrain category; TexC = texture category; Drain_R = drainage class; Gully_R = gullies category; _R indicates categories have been simplified for regression analysis.

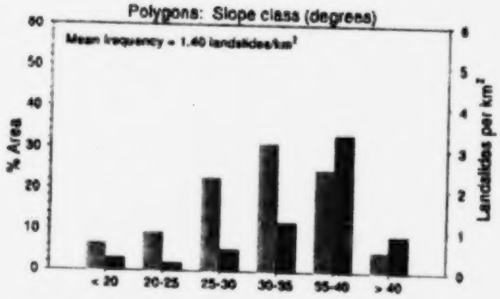

FIGURE 12 *Terrain map study areas, development-related landslides. Landslide density by slope class. Left bars (grey) are areal distribution; right bars (coloured) are landslide density.*

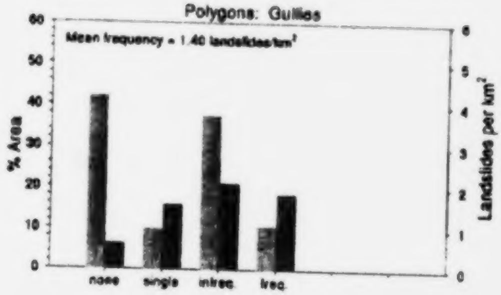

FIGURE 13 *Terrain map study areas, development-related landslides. Landslide density by gullies category.*

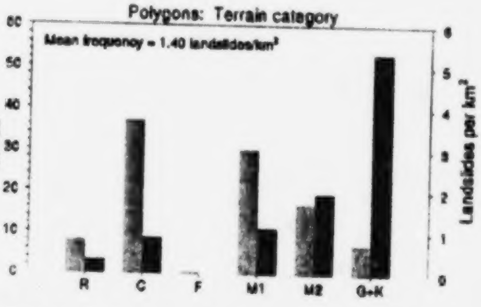

FIGURE 14 *Terrain map study areas, development-related landslides. Landslide density by terrain category. Categories are rock, colluvial, fluvial, shallow morainal, deep morainal, glaciofluvial/kame.*

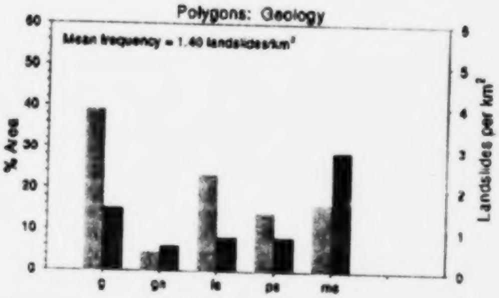

FIGURE 15 *Terrain map study areas, development-related landslides. Landslide density by geology category. Categories are granite, gneiss, fine sedimentary, Precambrian sedimentary, metasedimentary.*

Slope As with the southwest data set, landslide density increases up to the 35–40° slope class. This one category has an unexpectedly high density. The relatively high density in the < 20° category is probably due to random error in assigning points to grid cells (see Figures 3 and 4). It is possible that the statistical significance of slope is less than in the southwest data set because most of the areas in the < 20° category have been removed from the analysis, and because steep slopes predominate in the data set (compare the histograms in Figures 8 and 12).

Gullies Figure 13 shows that there is a large difference in landslide density between "no gullies" and any of the "gullies present" categories. This is consistent with the CHAID results and with field observations.

Terrain Category Figure 14 shows strong differences between categories, with the glaciofluvial/kame category much higher, and deep morainal next. This is consistent with the CHAID and logistic regression results for the random point data set, and with field observations. It is not evident why terrain category was of lower significance with the terrain polygon CHAID run.

Geology The metasedimentary category has the highest landslide density, consistent with the CHAID results. This category is represented mainly by the Lardeau Group, a geologic unit that is known from field experience to have a high incidence of slope stability problems, both in bedrock and surficial material. This instability reflects weak bedrock such as phyllite and mica schist, and soil that is rich in clay and mica. As in the southwest data set, there is also a relatively high landslide density in the granitic category.

Drainage Class Although this shows up as a significant variable, the result may be spurious. There is no consistent increase of landslide density with increasingly moist classes, as would be expected; there is no apparent reason why moderate drainage should rank higher than both well and imperfect drainage. Probably the sample sizes shown in Table 4b are too small for the result to be meaningful.

Roads and Logging in Polygon Although not a very precise variable, the presence of roads is significant in the polygon CHAID analysis. This is expected based on field experience, as most development-related landslides are due to road fills or drainage. The presence of logging was less significant.

CONCLUSIONS

In general, the results of statistical analysis for the two data sets show that slope, terrain category, and bedrock geology are significant terrain variables, in explaining the density of development-related landslides. These results are consistent with field experience. The presence of forest development, as defined by the development polygons, is a very significant variable in the overall landslide density. In the southwest study area, landslide density was over 6 times greater in development polygons than in undeveloped areas (0.32 vs. 0.05 Ls/km^2). In the terrain map study area, the presence of roads was a significant variable, but the presence of cutblocks was less significant. This is consistent with field observations that many landslides occur some distance below roads and cutblocks, and that roads are a much more common cause of landslides than cutblocks.

The above analysis results are preliminary. Further experimentation with CHAID and logistic regression is necessary to resolve some of the issues with inconsistent results, especially in the terrain map study areas. Also, further analysis is needed to examine variables that are significant for natural landslides compared with development-related landslides.

There were some large differences in results between the two data sets, especially with the importance of slope. Slope was much more significant for the southwest data set. This may be because a large part of this study area was low-slope terrain (< 20°) that has very few landslides, while the terrain map study area was mostly steep terrain. It is possible that the importance of slope may be mainly the difference between gentle slopes, which have almost no landslides, and all the steeper slope classes, rather than the differences among the steeper slope classes.

The landslide densities are greater in the terrain map study area, even when it is stratified by slope class and terrain or soil category. The map areas were selected because they had abundant landslides; however, the fact that densities are greater even when stratified suggests that there may be some other factors affecting landslide density that were not included in the analysis. As most of the feasible terrain attributes have been examined, the responsible factors are probably related to development. Intangible factors such as wise or unwise road location, road construction practices, drainage control, and quality of maintenance can greatly affect the probability of landslides. Several of the eight map areas contain many landslides on a few short sections of roads that were, because of either limited access options or poor planning, located in unstable terrain. Multiple landslides in a single polygon or on a short length of road can greatly increase the average landslide density in a study area, but they may be due to poor engineering practices rather than the inherent susceptibility of the terrain to landslides.

Terrain category was a significant variable in the terrain map study area. The glaciofluvial and kame categories had the highest landslide density, followed by the deep morainal category. This has implications for assigning hazard classes in terrain stability mapping. In the southwest study area, which is not covered by terrain mapping, soil category was used in its place. This was only marginally significant, which perhaps indicates that the soil mapping (which is at 1:50 000 scale and has little field checking) is a poor substitute for terrain mapping.

Of the two data sets analyzed, the terrain map data set is of higher quality because it is field checked and landslide positions are more precise. However, the sample size is much smaller than the southwest data set.

In the southwest data set, landslide densities in the more landslide-prone categories are typically 1–2 Ls/km^2 (number of landslides per km^2), while in the terrain map data set they are typically 2–6 Ls/km^2. Average densities for the whole data sets, excluding the < 20° areas, are 0.63 and 1.4 Ls/km^2, respectively. In areas of coastal British Columbia where terrain attribute studies have been done, typical landslide densities in clearcuts, averaged over the whole data sets, are 0.8–1.2 Ls/km^2 in the Coast Mountains, and 8–17 Ls/km^2 on the Queen Charlotte Islands and the west coast of Vancouver Island (Rollerson et al. 2001). This comparison suggests that development-related landslide densities in the Arrow and Kootenay Lake Forest Districts are comparable with those in the Coast Mountains, and an order of magnitude lower than on Vancouver Island and Queen Charlotte Islands. Most of the coastal studies do not include roads, only landslides in clearcuts, the density of which is very low in this study. Another factor is the time base of the sample; in this study it is about 30 years (i.e., landslides up to 30 years old can be identified on air photos and in the field), while on the Coast it is about 15 years. Because the data sets are dissimilar, it is difficult to make a comparison; however, it is probably safe to say that average development-related landslide densities in this study are somewhat less than in the Coast Mountains, and much less than on the coastal islands.

ACKNOWLEDGEMENTS

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REFERENCES

Bergerud, W.A. 1996. Introduction to logistic regression models, with worked forestry examples. B.C. Min. For., Victoria, B.C. Biometrics Info. Handb. No. 7. Work. Pap. 26.

ESRI Inc. 1996. ArcView version 3.2 and Spatial Analyst version 1.1 [computer programs]. Environmental Systems Research Insitute Inc., Redlands, Calif.

Guthrie, R.H. 2002. The effects of logging on frequency and distribution of landslides in three watersheds on Vancouver Island, British Columbia. Geomorphology 43:275–94.

Jordan, P. 2001. Regional incidence of landslides. *In* Proc. Watershed Assessment in the Southern Interior of British Columbia. D.A.A. Toews and S. Chatwin (editors). B.C. Min. For., Res. Br., Victoria, B.C. Work. Pap. 57/2001, pp. 237–47.

Roberts, W.B. 2001. A terrain attribute study of helicopter logging-related landslides in the southwest Coast Mountains of British Columbia. Unpubl. M.Sc. thesis. Simon Fraser Univ., Burnaby, B.C.

Rollerson, T. 1992. Relationships between landscape attributes and landslide frequencies after logging: Skidegate Plateau, Queen Charlotte Islands. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 76.

Rollerson, T. and T. Millard. 1998. Landslide-prone locations: the glacial and northern regions. Paper presented at Landslides and Forestry – Managing the Risk. Western Forestry and Conservation Assoc., May 6, 1998, Beaverton, Oreg., pp. 39–55.

Rollerson, T., T. Millard, C. Jones, K. Trainor, and B. Thomson. 2001. Predicting post-logging landslide activity using terrain attributes: Coast Mountains, British Columbia. B.C. Min. For., Vancouver Forest Region, Nanaimo, B.C. Tech. Rep. TR-011.

SAS Institute Inc. 1995. JMP version 3 [computer program]. Cary, N.C.

Schwab, J.W. 1988. Mass wasting impacts to forest land: forest management implications, Queen Charlotte Timber Supply Area. *In* Proc. Degradation of Forest Land: "Forest Soils at Risk." J.D. Lousier and G.W. Still (editors). 10th B.C. Soil Science Workshop, Feb. 1986. B.C. Min. For., Res. Br., Victoria, B.C. Land Man. Rep. 56, pp. 104–15.

SPSS Inc. 1997. SPSS version 8.0 and Answer Tree version 2.0 [computer programs]. Chicago, Ill.

Sediment Coring at Swansea Point Fan Delta, Mara Lake, British Columbia—Application of a Coring Method to Determine Historical Debris Flow Events

TED FULLER

ABSTRACT

A large landslide flowed down Hummingbird Creek to Mara Lake in July 1997. Archival research and historical map and air photo investigations suggested that other flood or debris flow events have occurred since the mid-1930s. The community of Swansea Point and Highway 97A are located on this fan delta. There is a need to determine magnitude and frequency of debris flows impacting alluvial fans in the southern Interior of British Columbia and this offers one example. Sediment coring with a modified Livingstone corer was used in Mara Lake to obtain metre-long cores around the perimeter of the fan. Cores were logged and measured for magnetic susceptibility. Samples from one core were analyzed for geochemical signatures. No dating of the cores has been done but Cesium^{137}, Lead^{210}, and radiocarbon dating could be applied to this material. Features that are interpreted as debris flows entering Mara Lake are thin layers of woody debris and sediment with coarser than average grain size. Magnetic susceptibility shows discrete "events" in several of the cores. Lake sediment sampling for effects of natural disturbance and forest development on fan deltas show promise for deciphering historical changes in sediment input. These sedimentation events may be related to seasonal flooding, landslides, fire, or forest development.

INTRODUCTION

Debris flows can travel down stream channels and deposit on fan deltas both in the subaerial and subaqueous environments. Thus, they have the potential to be preserved in the sedimentary record. The subaqueous sedimentary environment is best evaluated using the procedures of sediment coring that do not significantly alter the sediment profile. The cores can be read like a book; the beginning of the chapter is at the base of the core and the end is at the top. By examining the layers of sediment, the geologist can decipher the processes that occurred on the fan.

The questions addressed in this paper are (1) How frequently do large debris flows run out and deposit in Mara Lake? (2) What is their magnitude? (3) What can the lake sediment tell us? and (4) How well can lake sediment coring be used for process geomorphology?

The community of Swansea Point is located 7.5 km south of Sicamous on

Highway 97A and 20 km northeast of Salmon Arm. It is built on an alluvial fan at the front of a steep Interior mountain range called the Hunters Range in the Shuswap Highland (Holland 1964) (Figure 1). Drainage to the fan apex is from Hummingbird Creek (16.5 km^2 area) and Mara Creek (20.9 km^2 area). Mount Mara, at about 2190 m elevation, is the highest point in the watershed. Hummingbird Creek is entrenched in a bedrock-controlled structure resulting in an inner gorge. The mainstem length is 13 km. The drainage appears to follow structural lineaments from Eocene age block faulting of the Shuswap Metamorphic Complex, now mapped as the Eagle Bay Formation (Johnson 1990).

Hunters Range is at the periphery of the wet belt, with its hydrology dominated by snowmelt and rain-on-snow events associated with warm temperatures. The biogeoclimatic zones represented here, in the order of areal coverage over the drainages, are Northern Monashee Wet Cold Engelmann Spruce–Subalpine Fir variant, Thompson Moist Cool Interior Cedar–Hemlock variant, and Alpine Tundra (Lloyd et al. 1990). This area has a history of flooding, bridge washouts, and road relocations (Kamloops Sentinel 1935). The Eagle River and Perry River valleys to the north of Hunters Range had active deposition on several fans during the summers of 1965–1967 (Smith 1969). Pre- and post-Forest Practices Code forestry development were carried out on gentle-over-steep terrain above. Gentle-over-steep refers to a concave upper slope profile with lower slopes lying topographically above steeper slopes with a distinctive break in slope.

The fan is about 0.6 km^2 in area, with its apex near the confluence of Hummingbird Creek and Mara Creek (Figure 2). The channel across the fan flows south at present but has migrated historically. At the time of the Railway Belt surveys in the late 1800s to early 1900s, Hummingbird Creek flowed directly west to Mara Lake (Figure 3). During World War I, an internment camp was located on what was called Six Mile Point. Hummingbird Creek flowed more southwesterly at that time. A 1928 federal government air photo shows Hummingbird Creek following a meandering planform across

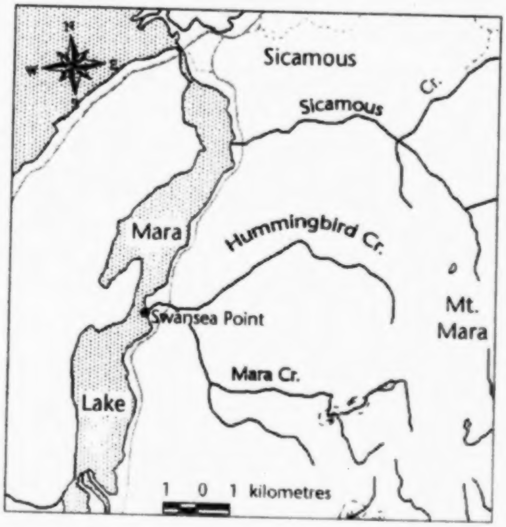

FIGURE 1 *Location map of Mara Lake.*

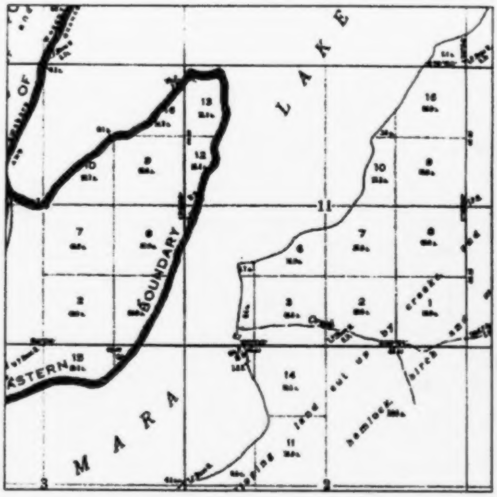

FIGURE 2 *Historical map of Mara Lake from the late 1800s to early 1900s from the Railway Belt Survey.*

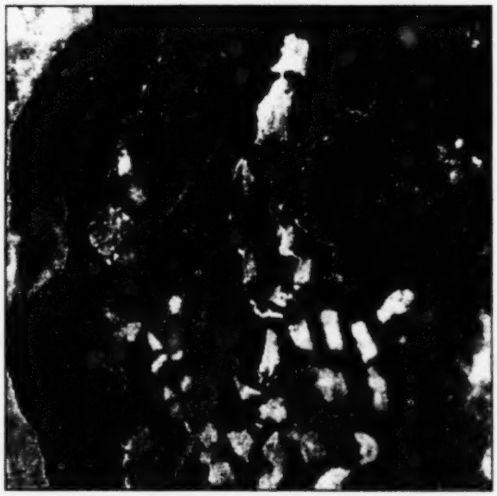

FIGURE 3 *Pre-1997 satellite image of Mara Lake, Swansea Point, and Hummingbird Creek showing development of the fan delta and forest harvesting and road building in the watersheds.*

the lower fan and discharging into Mara Lake in the southwest. The reach of Hummingbird Creek below the apex was broader in 1928. In the Depression years of the early 1930s, a work camp was re-established here but abandoned in 1935. Coincidentally, newspaper accounts report widespread flooding in 1928, 1935, and 1936 (Okanagan Commoner 1928; Enderby Commoner 1935; Kamloops Sentinel 1936). The more recent changes in Hummingbird Creek are recognized by comparing the 1994 air photos with the 1997 air photos. The reach below the apex has returned to its wide, bare gravel braided morphology.

METHODS

The tools to collect lake sediment cores are varied and have been honed by years of research, particularly in paleoenvironmental work. Many researchers use a method of non-disruptive coring (e.g., Arnaud 1997; Pettigrew 1999; Lamoureux 2000). For Mara Lake, the modified Livingstone corer and Kajak-Brinkhurst corers were used. These are widely used in lake sediment sampling for biological purposes.

FIELD WORK

Coring was carried out around the periphery of the fan in water depths ranging from 14 to 27 m in October 1999 (Figure 4). Core locations were centred on areas of former stream mouths. A motorboat and raft were used with a crew of between three and four persons. The core recovery procedure used

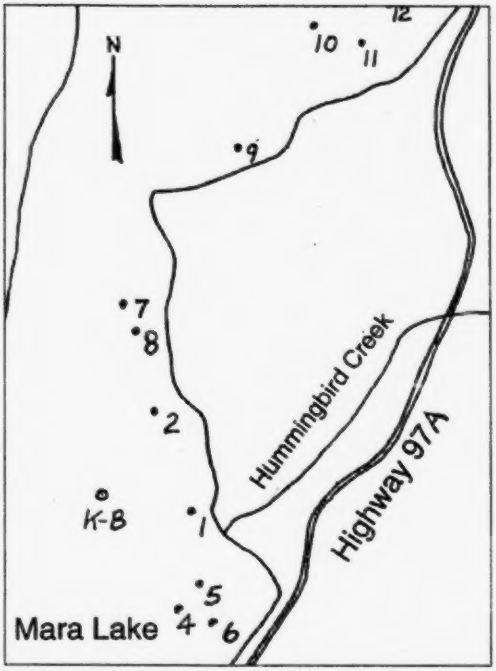

FIGURE 4 *Mara Lake sediment core locations around the periphery of the fan delta. K-B refers to the Kajak-Brinkhurst gravity core sample site.*

here was a raft, equipped with anchors at its corners, to move the coring device around the perimeter of the fan. The motorboat was used to tow the raft, and take bathymetry measurements and gravity core samples. The position of the raft was calculated by triangulation using a digital range finder and Brunton compass on fixed positions on land. The cores were collected from each site, extruded and wrapped in plastic film and aluminum foil, and placed in wooden core boxes. Gravity samples were also taken in deeper water beyond our limit of coring.

The modified Livingstone corer is a piston-type corer and was recommended for lake sediment sampling to get metre-long and longer cores (Dr. I.R. Walker, Biology Dept., Okanagan Univ. College, Kelowna B.C., pers. comm., 1999). The inside diameter of the core barrel is 5 cm. It is lowered to the bottom of the lake using rods that are screwed together and pushed into the substrate by the weight of the operators. It is restricted to lake depths that do not exceed the length of drill rod available. The Kajak-Brinkhurst corer is a gravity corer for less than 1 m long cores. The Kajak-Brinkhurst has a 6.25 cm inside diameter. It is dropped from the side of the boat in deep water (33 m) and a messenger weight is sent down the line to trigger a plunger, which seals the top of the Plexiglas core tube. The corer is then pulled up, capped, and brought to shore for extrusion.

The cores were stored in Kamloops, then transported to the sediment laboratory at the Pacific Geoscience Centre in Sidney on Vancouver Island. The K-B core was extruded in 1-cm disks using a specially built core extrusion device and stored in zip-lock bags.

ANALYSIS

Core Logging

Examination of the sediment cores was done in the sedimentology lab after discussion with Kim Conway, Geological Survey of Canada scientist. The physical characteristics of texture, lithology, colour, stratigraphy, and vane shear stress were measured. The Munsell soil colour chart was used to determine colour (Munsell Color 1990). Identification of the 1997 event was made in the uppermost section of the core samples. In addition, a similar size or smaller sedimentary record of a recent event underlies the presumed 1997 debris flow event. Closer to the base of the core, a third event was noted.

Magnetic Susceptibility

Magnetic susceptibility analysis determines the relative amount of magnetic minerals in the sediment, and helps to classify the sediment based on its mineralogy. It is a measure of the ease of magnetization, which is related to the concentration and composition of magnetizable material in the core. This tool appears to have found two more events that are correlated from core to core. If these sedimentary events are also debris flows or debris floods, they show that over a 1-m section of core, up to five events are present.

The sedimentology lab of the Geological Survey of Canada in Sidney was used for core scanning. A magnetic susceptibility (MS) scanning system[1] comprised of a coil connected to a personal computer and software was used to measure MS along the core axis. The frequency was set at 300 Hz for sediments. Eleven cores, ranging in length from 20 to 98 cm, were analyzed in this manner (Figure 5).

Chemical Analysis

Sub-sampling of core ML-99-7 in continuous 5-cm increments was done for the entire length of the core. A multi-element geochemical analysis was done for this core, from the centre of the fan delta front. The method used was induced coupled plasma (ICP) mass spectrometry. Included in the suite of elements were copper, lead, iron, and zinc, as well as loss on ignition (e.g., Figure 6).

DISCUSSION

The sediment cores collected around the fan delta of Hummingbird Creek (Swansea Point community) provide the following information. In general, the material cored is gyttja and sand with more or less distinctive layers of silty sand and organic litter. Gyttja is a freshwater lake sediment with abundant organic debris. Grain size appears to increase upward in the core (prograding fan). The magnetic susceptibility documents repeated phases of increased magnetic property of the sediment, which are referred to here as "events." The most recent large event to hit Mara Lake from Hummingbird Creek was the July 11, 1997, debris flow (Jakob et al. 2000). The record of this debris flow is interpreted to be the top of the sediment pile. A coarser sand layer is overlain and underlain by finer sand and capped by a thin layer of organic litter. This sequence is identified with debris flow and debris flood.

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[1] Version 1.0 27/IX/1996 Sapphire Instruments SI2 susceptibility metre, program written by Randolph J. Enkin based on SUSC15 2/III1995.

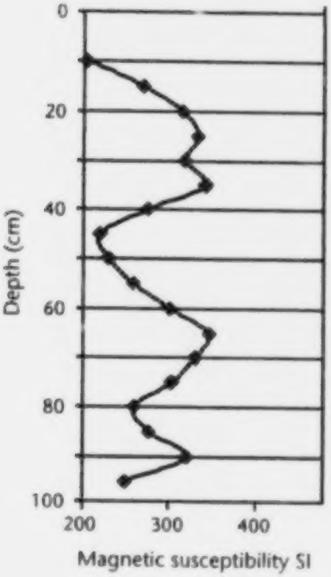

FIGURE 5 *Mara Lake Core 99-07.*

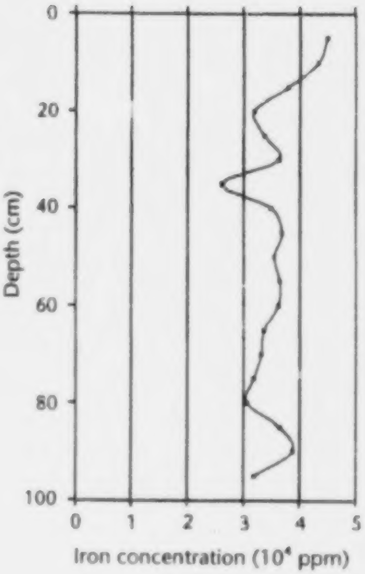

FIGURE 6 *Iron concentration in core 7.*

Since grain size analysis was not carried out due to the lack of sample volume required by the laboratory, a proxy of increased grain size with increased magnetic susceptibility was used. Magnetite grains are believed to be transported with the sand fraction onto the delta face. This was corroborated by visual and hand texturing of core material during core logging.

Down core chemical analysis was used to identify anthropogenic influence on the sediment. In the single core analyzed, this analysis shows increasing lead and copper levels in the uppermost part of this core. This result is broadly similar to that found in other parts of British Columbia, which document leaded gasoline use in the area (e.g., Mathewes and D'Auria 1982). Other metals have been plotted and may represent natural and human influences on the Hummingbird Creek and Mara Creek watersheds.

CONCLUSIONS

Lake sediment core sampling on fan deltas can be a useful method to determine anomalies in the lake sediment that may be caused by runoff events and debris flows or debris floods. The record is more complete than the terrestrial record. This is because the prevailing accumulation of sediment on the subaqueous portion of fans may not be recorded on the floodplain or is subsequently lost from future erosion. Relatively straightforward analysis by core logging, magnetic core scanning, sampling for chemical, mineralogical, and textural properties, and age determination from isotopes can potentially be done.

The identification of older debris flow deposits recorded in the lake sediment is based on that of the recent large 1997 event. Coarser-grained sediment overlain by fine woody debris with sharp basal contacts on fine lake sediment appears to be diagnostic.

The frequency and magnitude of debris flows impacting the fan and reflected in the sediment column indicate that the fan has a history of debris flows.

Without age control of the stratigraphy of the lake sediments, it is premature to speculate on the frequency of events that have impacted the fan/delta and presumably the fan itself. Other processes may be responsible for the change in sediment character in the fan. Forest fire, summer thunderstorms, rain-on-snow, road building, and creek avulsion can all add sediment to the delta.

ACKNOWLEDGEMENTS

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REFERENCES

Arnaud, E. 1997. The effects of forestry activity on sediment yield and recent lake sediments: Vancouver Island, British Columbia. *In* Proc. Ann. Meet. Geol. Soc. Am., Oct. 20–23, 1997, Salt Lake City, Utah. Abstracts with programs, no. 50283.

Enderby Commoner. 1935. Mountain streams on rampage. v. 28, n. 18, whole n. 1422, p. 1.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. B.C. Dep. Mines and Petroleum Resour., Victoria, B.C. Bull. 48.

Jakob, M., D. Anderson, T. Fuller, O. Hungr, and D. Ayotte. 2000. An unusually large debris flow at Hummingbird Creek, Mara Lake, British Columbia. Can. Geotech. J. 37:1109–25.

Johnson, B. 1990. Shuswap metamorphic complex. B.C. Min. Energy, Mines and Petroleum Resour., Geol. Surv. Br., Victoria, B.C. Open File 1990-30.

Kamloops Sentinel. 1935. May 3, July 2, July 5, July 9, and July 16.

———. 1936. May 5, June 2.

Lamoureux, S.F., 2000. Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves. Water Resour. Res. 36: 309–18.

Lloyd, D., K. Angove, G. Hope, and C. Thompson. 1990. A guide to site identification and interpretation for the Kamloops Forest Region. Part 2. B.C. Min. For., Victoria, B.C. Land Manage. Handb. 23.

Mathewes, R.W. and J.M. D'Auria. 1982. Historic changes in an urban watershed determined by pollen and geochemical analyses of lake sediment. Can. J. Earth Sci. 19(11): 2114–25.

Munsell Color. 1990. Munsell soil color charts. Revised ed. Kollmorgen Instruments Corp., Macbeth Division, Munsell Color, New York, N.Y.

Okanagan Commoner. 1928. Flood waters force people out of homes. v. 21, n. 12, whole n. 1055, May 31, 1928, p. 1.

Pettigrew, E.L. 1999. Isolating land use effects on hydrology and sediment yields using lake cores. *In* Hydrologic Change in South Central B.C. B. Guy and R. Winkler (editors). Canadian Water Resources Association – British Columbia Branch, Southern Interior Spring 1999. Abstract, p. 10.

Smith, G.W. 1969. Surficial geology of the Shuswap River drainage, British Columbia. PhD thesis. Ohio State Univ., Columbus, Ohio.

The Yalakom—A Valley, a River, and a Road: Doing Our Best to Maintain Access in High Consequence Terrain

GREG REID, RUSSELL MERZ, AND BRUCE HUPMAN

ABSTRACT

For reasons of geography and geology, some forest road corridors have and will continue to be located in very difficult and sensitive terrain, if there is to be any access to forest lands and resources. In previous decades, the primary concerns with difficult roads in difficult terrain usually related to their construction, and once built, to keeping them open for people to use. Today's society requires a broader approach, yet one that is applicable to a specific site, so that a road corridor does not inadvertently impact the integrity of the ecosystem elements it passes or provides access to. This presentation provides a case history of recent work conducted by the B.C. Ministry of Forests (MOF) in the Yalakom River watershed, studying the interaction of a forest road corridor, a dynamic river channel in a geologically immature valley, and the stability of slopes in between the two. In this study, consideration of the consequence of terrain instability, rather than hazard or risk, was used as the primary criterion for assessment of the performance of the road corridor and individual structures. Based on the consequence ratings developed, and the requirement of maintaining the integrity of the roadway in the long term, prescriptions were developed for a variety of remedial treatments to mitigate perceived concerns. The focus of this presentation is not on the actual prescriptions developed, but rather the rationale and methodology employed by the assessment team. The main element of the study was a combined channel and terrain stability field assessment along the road corridor, conducted jointly by a terrain hazard specialist and a hydrologist. The outcome of the study was to provide the MOF with an improved strategy for managing liability risk and terrain instability consequence, along a road corridor that traverses very challenging terrain in the Interior of British Columbia.

INTRODUCTION

In June 2000, Golder Associates Ltd. (Golder) commenced a study of the Yalakom River Forest Service Road (FSR) and Burkholder branches within the Yalakom River watershed located northwest of Lillooet, B.C. The study was directed towards lower valley slopes, including the river channel and road corridors, with technical assessment focused on aspects of runoff management, road maintenance, and mitigation of surface erosion potential along the road corridors reviewed. The main elements of the study include an overview sediment source and terrain assessment for the lower valley slopes;

assessment of relative consequence for identified sites; consideration of potential management, maintenance, and/or upgrading strategies; and development of recommended treatment prescriptions.

The objective of this project was to provide a rapid assessment of segments of the existing roadways considered to represent moderate to high risk for slope instability and sediment generation. Concurrent with the assessment was an associated requirement to prescribe appropriate remedial works and identify management practices to reduce soil erosion, improve hillslope hydrology where necessary, and maintain water quality. Based on these assessments and prescriptions, a consequence-based summary of recommended actions was produced.

STUDY AREA DESCRIPTION

The Yalakom River Valley

The Yalakom River valley is located approximately 50 km northwest of Lillooet, B.C. The 580-km^2 watershed consists of alpine ranges and upland plateaus, bedrock canyons, talus slopes, and large landslide lobes. The Yalakom River forms the boundary between two major physiographic regions: the Coast Mountains to the west and Fraser Plateau to the east. The west flank of the valley is formed by the eastern margin of the Shulaps Range, and the east flank of the valley is formed by the western margin of the Camelsfoot Range (Holland 1976).

The valley bottom approximately follows the alignment of a regional-scale fault, which separates clay-rich rocks of the Shulaps Ophiolite Complex to the west, from the fine-grained sedimentary rocks of the Jurassic age Jackass Mountain Group to the east. The fault trace is inferred to be north of the Yalakom River north of the Peritotite Creek confluence, and swings south of the Yalakom River north of the Yalakom Creek confluence (Schiarizza et al. 1997). The study area includes the upper 40 km of the Yalakom River valley, extending northerly to the divide with the Churn Creek watershed, southwest of Poison Mountain (Figure 1).

Several reaches of the river channel consist of well-incised bedrock canyons. There are also several reaches where at least one bank of the river channel is defined by large talus slopes, or termini of large earthflow landslide lobes. The Yalakom FSR ranges in elevation from approximately 700 m above sea level at the southern end of the study area (km 42.7) to 1750 m at the north end. The valley is canyon-like in many places and develops into progressively less relief at the upper elevations in the northwest portion of the watershed. The spur roads included in the study all provide access to parts of the undulating upland plateau on the east side of the Shulaps Range, southwest of the Yalakom River.

The Yalakom River

The Yalakom River is characterized as a fourth-order stream contributing to Bridge River downstream of the Terzaghi Dam. It provides the majority of the flow in Bridge River (Coulson and Obedkoff 1998). The watershed lies in the transition zone of the rain shadow of the southern Coast Mountains.

The Yalakom River is the only unimpeded flow component of the four major watershed systems that flow into the Fraser River from the west, near Lillooet. For this reason, the Yalakom River is an important tributary of the Fraser system for salmonid population spawning, rearing, and habitat.

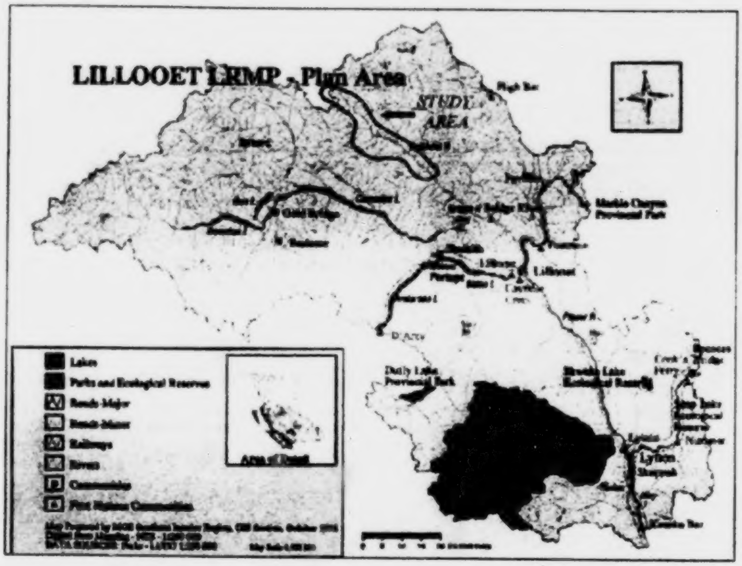

FIGURE 1 *Key map of the Yalakom River Valley.*

The hydrology of the Yalakom basin is a combination of that found in Coastal and Interior river basins as it lies in the Northern Cascade Mountain Hydrologic Zone. Being in a transition zone between the Coast Mountains and the Fraser Plateau, hydrologic conditions change markedly with elevation and distance upstream. Winter precipitation is generally in the form of snow, which accumulates as snowpack in the mountains in the watershed. Snowmelt leads to peak flows from May to August, declining through the autumn to a base flow level from January to March, with the exception of occasional heavy rainstorms from August to October.

The river generally exhibits a high channel gradient and a moderately high sediment load (bedload and suspended load), and lacks an extended floodplain due to its deeply incised nature. The river also has many reaches with active, naturally eroding banks, in locations where anthropogenic activity is both present and absent.

The Yalakom River FSR

The first 12 km of the road along the Yalakom River, beginning at the confluence with Bridge River, is managed by the B.C. Ministry of Transportation. The remaining 40-km segment of mainline Forest Service Road (FSR) and several spurs are managed by the B.C. Ministry of Forests (MOF), Lillooet Forest District office in Lillooet, and the licensee operating in the valley.

The Yalakom River FSR was constructed "pre-Code" (i.e., before the implementation of the Forest Practices Code in 1995). Parts of the alignment follow older mine exploration "cat trails." If this road were to be constructed today, it is unlikely that it would follow the same alignment as it comes too close to the river on steep terrain. The road corridor generally follows the valley-bottom slopes, moving from one side of the canyon to the other, where the least challenging terrain for road construction exists, but occasionally climbs higher up the valley side wall to avoid stretches of particularly difficult terrain. The road was constructed to attempt to follow remnant terraces, avoiding active talus areas, large-scale landslides, and bedrock bluffs. Accordingly, the mainline FSR is generally close to the river. The Burkholder spurs provide access to parts of the upland plateau west of the Yalakom River.

STUDY RATIONALE

The Yalakom River FSR has been identified as a required long-term mainline access corridor within the Yalakom basin of the Lillooet Forest District. This road crosses very challenging terrain, including large areas with steep slopes and/or natural terrain instability. Consistent with the principles implicit in the Forest Practices Code, the MOF is interested in employing appropriate strategies for maintaining the roadway in the long term. One such strategy includes identifying opportunities to employ "best management practices" to minimize potential impact on water quality along the more problematic segments of the corridor. Other objectives for the study included setting priorities for potential concerns, and developing recommendations for practical and objective management strategies for the concerns identified.

To accomplish these goals, an assessment of terrain instability and erosion potential was required along the road corridors in the study area containing the highest sensitivity, considering both hydrological and geotechnical aspects of the site.

ASSESSMENT METHODOLOGY

To realize the goals for the assessment, and carry out the work efficiently and cost-effectively, a project team including both a terrain hazard specialist and hydrologist was selected by Golder. To facilitate planning for the project, and development of an appropriate methodology for the study, a helicopter overflight of the road corridor and river valley was organized by MOF staff. In this way, the true scope of the project and nature of the site could be viewed first-hand, and a practical methodology and work plan could be developed.

The sensitive background of the study area was confirmed in the overflight. The study area contained a multitude of sites that would be considered high risk to the river ecology due to slope instabilities and other erosion sources. Based on discussions held between the project team and MOF staff during the site orientation, a consensus was quickly reached as to the work plan and deliverables required for the study. The main study elements were to include:

- a summary of concerns / potential problems identified;
- recommendations for management strategies, including maintenance items, remedial works, and, if appropriate, detailed prescriptions;
- priority rankings for implementation of any activities recommended; and
- updating of a culvert inventory, including performance assessment of all stream crossing structures along the Yalakom River FSR.

To provide a focus for the fieldwork, a terrain instability and erosion source survey was completed for the road corridors at the site, based on consideration of existing terrain stability mapping and review of air photographs.

In addition, Golder had access to previous reports completed on a 1 km long portion of the Yalakom River FSR that had recently been upgraded following some localized terrain instability in the late 1990s.

Consequence as an Assessment Criterion

Similar studies have sometimes included ratings and rankings of risk, hazard, and consequence for road segments, stream reaches, or terrain elements present at a site. To characterize a larger study area, practitioners often break up the study site into smaller elements or segments of similar character, based on the physical attributes present. In such studies, segments can be determined based on the terrain slope, landform element, soil and bedrock type, and proximity to a watercourse. Once all of these aspects have been tabulated, segments can be defined and individually assessed and rated for hazard, consequence, and risk. Then, based on the risk ratings obtained, prescriptions could be developed to address segments representing areas of concern, with higher priority given to segments with the highest rating.

The difficulty with following this approach in the Yalakom River FSR study area is that almost all of the mainline corridor would have a high to very high hazard rating, resulting from the nature of the terrain it crosses and proximity to the Yalakom River and tributaries. Consequently, following a traditional approach to hazard assessment would have required a considerable amount of field time just to properly document all of the physical attributes and define segments or smaller elements. Faced with limitations to our field time, an alternative approach was needed if the goals of the study were to be met for a reasonable level of effort.

Our approach to this study area was to consider the likely outcome of continued terrain instability in the immediate vicinity of the road corridor, if there were no changes made to the current condition of the site. Thus, the hazard for each site was assumed to be relatively constant, and the assessed outcome, or consequence, would provide an indirect risk rating. The consequence of change to each individual segment of the road corridor, adjoining slopes, and river channel defined the priority for work in the study area.

This type of assessment is really a consideration of particular aspects of the consequence of terrain instability. For this study, we considered two main types of consequence as being particularly relevant to the study area:

- impacts of terrain instability on the Yalakom River channel, in terms of water quality and riparian habitat; and
- impacts of terrain instability on the road corridor and infrastructure, in terms of user safety concerns.

Ratings were developed for each site that we identified as a potential concern, using the aspects of consequence as selective criteria. The level of concern and priority rating (low, moderate, high, etc.) developed was related to the nature, scale, and severity of anticipated disturbance of continued erosion or slope failure at each site. For example, a road shoulder subject to ongoing ravelling, where a moderate amount of sediment could be input directly to the river channel, would be considered as a low consequence. A greater consequence would be present at similar slopes where the river was naturally undercutting the slope toe and retrogression was occurring or progressively larger volumes of sediment could be generated. The highest level of consequence would be assigned to such sites where continued river erosion may result in sudden loss of part of the road surface, also representing a safety hazard to road users.

Using these aspects of "consequence," the implications of current conditions at the site posed by combinations of river erosion, terrain instability, and runoff water management (roadway/structure drainage patterns) could be rapidly compared and assessed. Following this methodology, the assessment team was able to quickly identify roadway segments or parts of the site with more significant concerns, and make the best use of our field time to consider sites with the highest consequence ratings in greater detail.

Field Assessment

In practice, assessment of each area identified in the initial erosion source survey was carried out sequentially, from south to north. Some areas were characterized rather quickly, using the consequence criterion described above as being of minor concern. For those areas where a concern was noted, the nature of the concern and site elements were described, location and extent noted or revised, and assessment carried out. In addition, other sites not evident on the initial sediment source survey were also identified and assessed during the fieldwork.

The result of each assessment was the development of site-specific management strategies or prescriptions to mitigate apparent hazards. The "best management practices" philosophy was used to identify suitable treatments as well as practical alternatives or options. Typically, more general treatments or prescriptions were recommended for low-priority sites, and more detailed prescriptions were prepared for higher-priority sites. In some cases a distinction was made between short-term performance and treatment, and longer-term performance of a particular area. Last, a priority rating was assigned for the main work activities recommended at each site.

STUDY OUTCOME

Following the methodology described above, the study was completed in the summer of 2000. Approximately 60 km of road corridor were assessed, which required 2 days of fieldwork. The initial terrain instability and erosion source survey identified 70 sites of potential concern. Through the assessment process, 28 of the 70 original sites were not considered significant in terms of the consequence criteria selected. An additional seven sites, which were not evident on the air photos, were added to the survey and assessed.

SAMPLE PRESCRIPTIONS

Examples of some of the prescriptions developed for various (i.e., low to very high) consequence and priority ratings are provided below.

Priority	**Low**
Reference	56 (Figure 2)
Flightline	97223: 031-3
Km marker	78.1
Feature	Road adjacent to river.
Pre-site visit comments	"Runoff management ok?"
Observations	Minor rilling present at road shoulder extending down onto erodable slope below, where a low grader berm is breached.
Work recommendations	Change the road alignment slightly—move in by 1.5 m. Re-establish new grader berm and ditch line to move road surface away from slope crest.

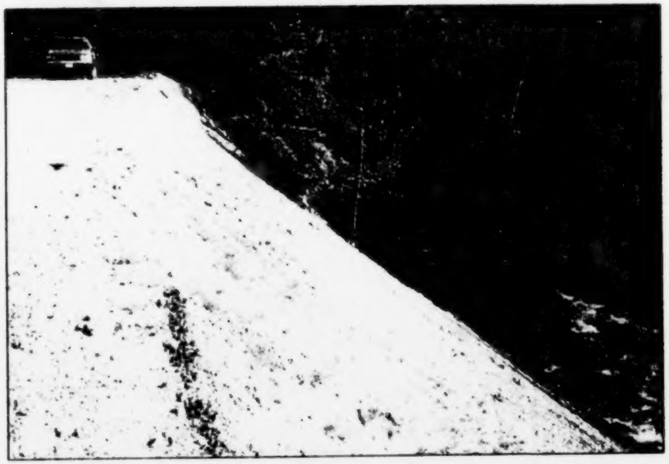

FIGURE 2 *View of road shoulder at Site 56.*

Priority	**Medium**
Reference	17 (Figure 3)
Flightline	97127: 073
Km marker	48
Feature	Sediment source below road, includes shoulder and fillslope.
Pre-site visit comments	"Slide toe area; assess condition."
Observations	Active slough/ravelling from flow / creep slide debris forms active sediment source to river, exacerbated by any debris placed on road shoulder / slope crest. Localized abundant seepage is present in slide debris exposed in road cutbanks.
Work recommendations	Improve insloping of road surface, and blade any big snowbanks off before spring thaw. Install backup culvert at ribboned location and place drainage blanket (drain rock apron) up against seepage area to improve cutbank stability.

FIGURE 3 *View of road corridor and river at Site 17.*

Priority	**High**
Reference	36 (Figure 4)
Flightline	97220: 227
Km marker	64.3
Feature	Sediment source below road.
Pre-site visit comments	"Runoff management ok? Assess sensitivity."
Observations	Large open slope of erodible material; river undercutting toe. Relatively large volume of sediment input to river→ high consequence site.
Work recommendations	Insloping and monitoring of road performance in short term. Realignment of 100 m of road in long term.

Priority	**Very High**
Reference	55 (Figure 5)
Flightline	97221: 156–8
Km marker	76.6
Feature	Road adjacent to river.
Pre-site visit comments	"Runoff management ok?"
Observations	The road surface width is restricted due to ongoing ravelling from upslope, and instability due to undercutting by the river at the toe of the slope. Active ravelling (chippy colluvium) slope above road, locally extends below road, at N end right into river. River scour is undercutting bank below the road, near the N end of the lock block wall on the inside of the road—8 m length of road shoulder has already been lost. Catchment area behind lock blocks is completely full and some overspill has occurred.
Work recommendations	At S end (km 76.5), install log crib or other structure to stabilize road shoulder / slope crest for 20 m length. Install cross-drain culvert (stake and ribbon), and armour inlet. At N end (km 76.7), place rip-rap armour—see detailed prescription/comments for this site (see Figure 6 below). Clean out N end of lock block wall to re-establish debris catchment area.

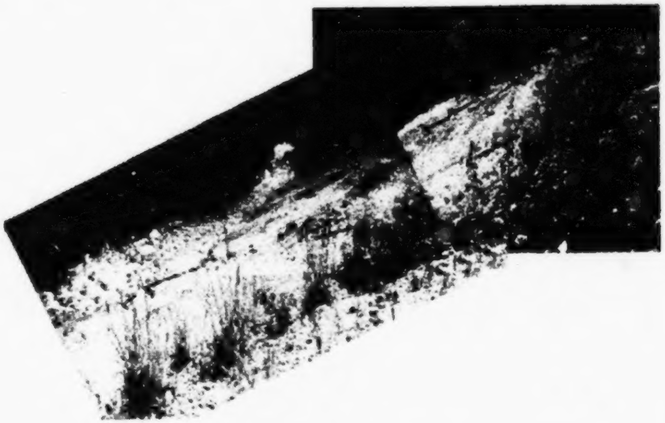

FIGURE 4 *View of sediment source and slope at Site 36.*

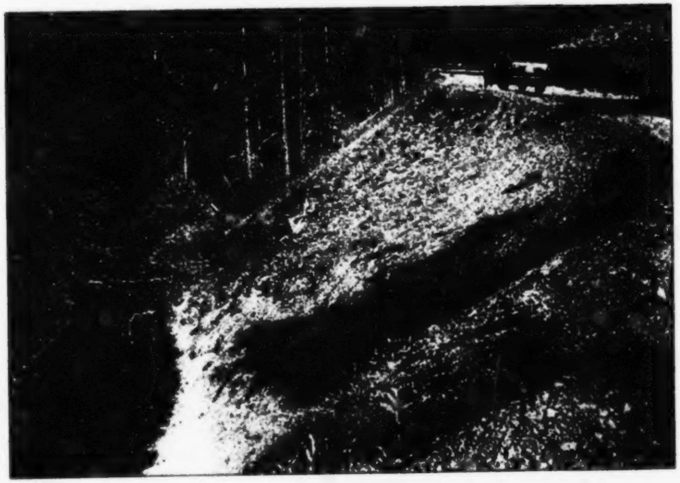

FIGURE 5 *View of very high priority area at Site 55.*

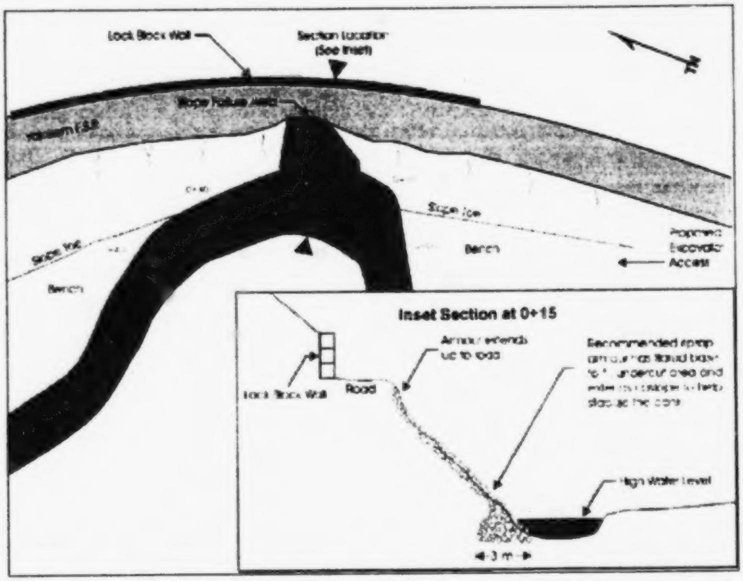
Lock Block Wall
Section Location
(See Inset)
TN
Slope Failure Area
Slope toe
Slope toe
Bench
Bench
Proposed
Excavator
Access
Inset Section at 0+15
Armour extends
up to road
Recommended riprap
Lock Block Wall
Road
High Water Level
3 m

FIGURE 6 *Example of plan and section prepared for detailed prescription for Site 55.*

SUMMARY

In the authors' opinion, pursuit of a more conventional approach in conducting this study would have required completion of several independent assessment procedures, taken more time, and been more costly than the approach chosen. The approach adopted provided for timely and cost-effective delivery of the information requested, so that the MOF could begin to implement the recommendations in a timely manner.

Allowing the contributing professionals freedom to review the site and decide on an appropriate strategy for carrying out specialized assessments provided more timely results, which were better suited to the conditions/demands of the study area.

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The authors wish to thank the B.C. Ministry of Forests and Golder Associates for the opportunity to participate in the project and prepare this presentation. We would also like to thank our reviewers for their contributions and improvement of this document.

REFERENCES

Coulson, C.H. and W. Obedkoff. 1998. British Columbia streamflow inventory. B.C. Min. Environ., Lands and Parks, Resour. Inventory Br., Victoria, B.C.

Holland, S.S. 1976. Landforms of British Columbia: A physiographic outline. B.C. Dep. Mines and Petroleum Resour., Victoria, B.C. Bull. 48.

Schiarrizza, P., R. G. Gaba, J. K. Glover, J. I. Garver, and P. J. Umhoefer. 1996. Geology and mineral occurrences of the Taseko - Bridge River area. B.C Min. Employment and Investment, Geol. Surv. Br., Victoria, B.C. Bull. 100.

Drainage Plans: A Comprehensive Planning Tool in High-Risk Terrain

K. GREEN AND W. HALLERAN

ABSTRACT

Drainage plans can be a powerful tool in the proactive management of terrain instability events. The methodology used to undertake drainage plans is currently non-standardized, which results in products being submitted that vary greatly in quality and cost. To achieve some standardized approach, resource managers and the professionals who conduct the plans must agree on their objectives, components, application, and implementation. The drainage plans are used to delineate drainage patterns over a hillslope, including the location of drainage divides and watercourses (perennial and ephemeral). In addition, drainage plans are used to locate culverts or cross-ditches along high-risk road segments that will maintain or re-establish natural drainage patterns. It is suggested that a risk analysis approach (where Risk = Hazard × Consequence) be used by resource managers to determine where drainage plans are appropriate. Drainage plans should be considered where there is a high or very high risk (moderate or high-hazard and a high consequence) of a slide occurring on or below the area where development or deactivation is proposed. To accurately locate watercourses and drainage divides, a three-step methodology is suggested, which includes a preliminary air photograph review, detailed fieldwork, and accurate presentation of the information for easy incorporation into operational plans. As a minimum, the drainage plan deliverables should include watercourse and divide line work transferred onto an accurate topographic base map and flagged in the field. Experience indicates that incorporating information from a drainage plan into operational plans is the most difficult aspect of all. If drainage plans are to be successfully used as a tool for minimizing development- or deactivation-related slides in high-risk areas, all levels of management—from planners to operations supervisors to hoe operators—must be made aware of where and why the plans are being undertaken.

INTRODUCTION

Comprehensive study of landslides and their causes is ongoing in the Nelson Forest Region, located in southeastern British Columbia. Preliminary findings indicate that most development-related landslides (at least 33% and possibly as high as 69%; Table 1) in British Columbia's southern Interior occur as a result of drainage diversion and concentration along resource roads (Jordan 2001).

TABLE 1 *Landslide study data, Nelson Forest Region (Jordan 2001)*

Total number of landslides:	582
natural	135
development-related	447
Distribution by apparent cause:	
road fill[a]	36%
drainage diversion, road	25%
drainage diversion, skid trails	8%
road cut	2%
clearcut	2%
other	4%
natural	23%

[a] Many caused by water diversion flowing over and saturating fillslope.

In British Columbia, the Forest Practices Code regulations require road designs and prescriptions to maintain slope stability when roads are proposed on potentially unstable or unstable terrain. Drainage structures are prescribed as part of the road design to maintain natural drainage patterns along a proposed road right-of-way.

Although most road surveys locate drainage structures for permanent watercourses, the location of short-duration (ephemeral) watercourses, which often have no obvious channel (also referred to as non-classified drainages or NCDs), are commonly missed during road surveys that are undertaken after the freshet. Drainage divides that form the natural topographic separation between these small sub-basins may also be ignored. As a result, intercepted ditch water often flows across subtle drainage divides before being discharged from the road prism.

The location of ephemeral watercourses and the location of drainage divides are two pieces of information that are essential for reducing the number of resource road–related landslides in the southern Interior. These two pieces of information are also critical for maintaining slope stability where roads are proposed above potentially unstable or unstable terrain.

Drainage plans that identify the location of watercourses and divides can be an effective tool in pre-emptive management of terrain instability events related to resource road construction or deactivation. This paper introduces the concept of drainage plans, presents methods and deliverables that have been used by the authors over the past 3 years, and discusses difficulties that have been encountered in the application and incorporation of drainage plan information into operational plans and activities.

DRAINAGE PLAN OBJECTIVES

A drainage plan is a map that delineates surface drainage features, including watercourses and divides over a hillslope. The primary objectives of a drainage plan are:

- to identify drainage features over a slope; and
- to locate drainage structures to minimize drainage diversion and concentration and reduce the occurrence of slides caused by drainage diversion and concentration.

Secondary objectives can include:

- locating drainage structures to avoid saturating areas were there is existing downslope instability; and
- delineating areas for hydrological risk assessment of proposed forest development activities.

Roads and trails constructed with cutslopes less than 0.5 m can intercept surface and subsurface flows. A road that traverses a slope at a constant grade cuts through gentle topographic swales and ridges that originally functioned to maintain disperse surface and subsurface flows. The identification of these subtle features allows for placement of drainage structures that reduce the opportunity for water carried in the ditch line to be diverted across divides. In addition, identification of ephemeral surface flows and the corresponding divides (micro-drainages) on the face of slopes allows for a more precise assessment of level of harvest within these micro-drainage basins where downslope terrain stability is a concern. Identification of these micro-drainages also allows drainage structures to be placed so that culvert discharge can be avoided or minimized on slopes where downslope terrain instability is identified.

INFORMATION REQUIREMENTS

The information required to complete a drainage plan includes an understanding of the nature of drainage over the hillslope, the location of permanent and seasonal watercourses, the location of drainage divides, and the location of existing drainage diversions.

Nature of Slope Drainage

Hillslope drainage patterns are dependent on cross-slope and longitudinal slope profiles, soil depth (i.e., depth to restricting layer), relic glacial landforms, and bedrock structure.

Slope Profile Slope profile generally plays the most significant role in controlling the overall drainage pattern (Figure 1). Convex slopes can have complex drainage patterns, including divergent drainage patterns that occur when small unconfined streams pool behind and split around obstructions such as bedrock knolls or overturned root wads. Drainage divides on convex slopes are subtle and often discontinuous. Convergent drainage patterns occur on concave slopes where ephemeral streams converge downslope, becoming larger and more entrenched. Drainage divides on convex slopes generally converge downslope and become more defined.

Soil Depth Groundwater and interflow in unsaturated soil (vadose zone) can play a significant role in slope drainage patterns in areas with shallow soils or restricting layers. These conditions often exist on convex slopes where the processes of glaciation have scraped the noses of the upper convex slopes bare of soil. Seeps and springs can develop where subsurface and groundwater flow is concentrated through shallow soils (Figure 2).

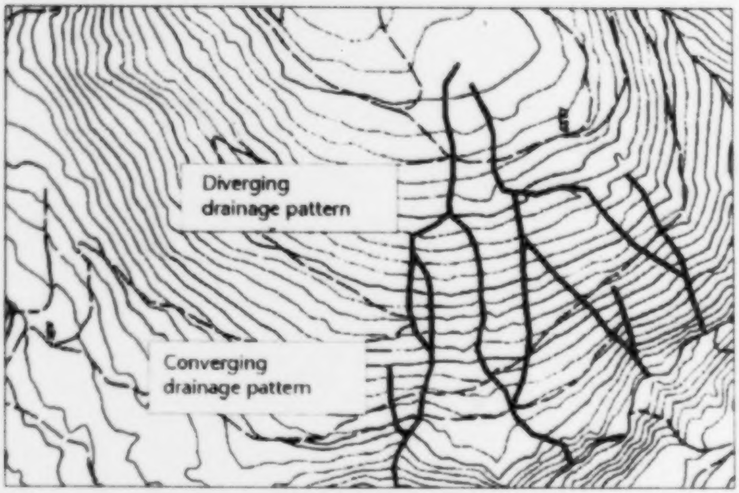
Diverging drainage pattern
Converging drainage pattern

FIGURE 1 *Simplified representation of drainage patterns on convex and concave slopes.*

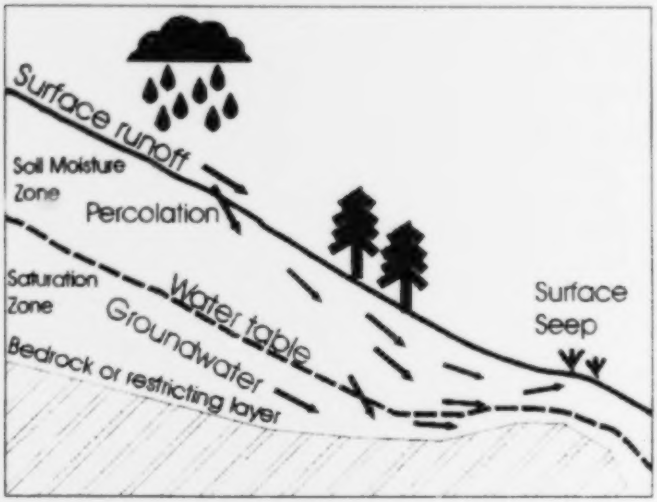
Surface runoff
Soil Moisture Zone
Percolation
Saturation Zone
Water table
Groundwater
Bedrock or restricting layer
Surface Seep

FIGURE 2 *Subsurface and groundwater flow can account for a significant proportion of slope drainage in some areas. Seeps develop where subsurface water is brought to surface.*

Glacial Landforms About 11 000–20 000 years ago, massive valley glaciers and ice sheets covered most of the lowland areas and occupied all of the large British Columbia Interior valleys. During deglaciation, rivers and streams flowed on top of and along the margins of the melting glaciers and from the toes of the glaciers. Sediment scoured from beneath the glacial ice was deposited over the landscape as the ice downwasted. A ridged and hummocky topography formed by the glacial sediments is often exposed at the mid-elevations along the main Interior valleys and on the valley sides and interfluves of larger tributary valleys. In some locations, these ridges and hummocks control surface drainage patterns (Figure 3).

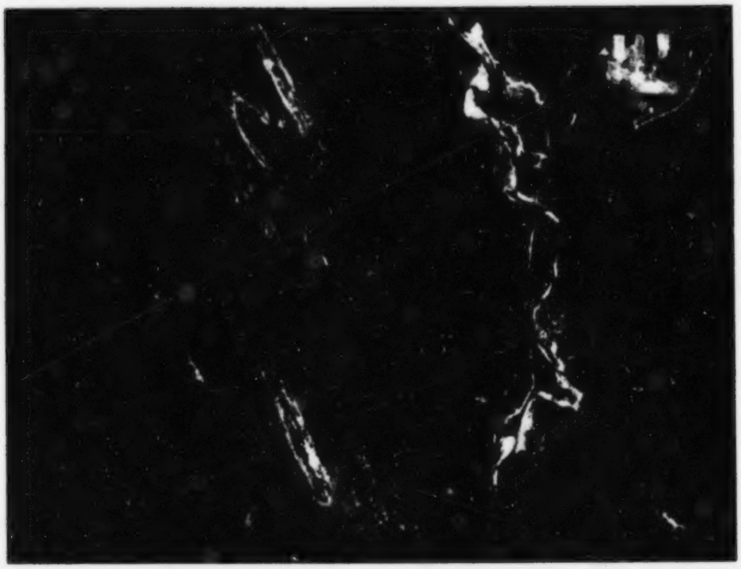

FIGURE 3 *Relic glacial topography controlling surface drainage patterns.*

Bedrock Structure Faulted, jointed, and foliated metamorphic and sedimentary rocks and, to a lesser extent, intrusive rocks underlie much of the landscape throughout the southern Interior of British Columbia. Where soil is shallow and bedrock is exposed or close to the surface, joints and fractures in the rock can control surface and subsurface drainage patterns (Figure 4). Locating permanent and ephemeral streams and the divides that separate them is essential to maintaining natural drainage patterns over a hillslope. Permanent watercourses are usually identifiable on air photos and on the ground. However, the locations of permanent watercourses on digital base maps are often incorrect and need adjusting.

FIGURE 4 *Rectangular jointing in weakly foliated metamorphic rocks in the Castlegar area.*

FIGURE 5 *Ephemeral stream flowing over the forest floor.*

Location of Ephemeral and Permanent Watercourses and Divides

The location of ephemeral or seasonal streams may be identifiable on air photos but many are difficult to identify on the ground due to the lack of defined channels. In many cases, ephemeral streams flow over the forest floor (Figure 5), leaving little evidence of a channel once the flows cease.

Location of Existing Drainage Diversions

If natural drainage patterns have been previously disrupted by old roads and trails, additional road or trail construction can compound existing drainage diversion and concentration (Figure 6). Where there has been a significant amount of past road or trail development on a hillslope, it may be necessary to start at the top of a drainage basin and work downwards to identify the extent of existing diversions.

SUGGESTED METHOD AND OUTPUTS

Three steps are suggested to complete a drainage plan. The first step is to delineate all obvious watercourses and divides on recent 1:20 000 (or larger) air photos. Where significant development has occurred, older air photos can be used to help identify original drainage patterns.

The second step is to conduct fieldwork to verify and/or correct watercourse and divide locations on air photos and identify on the ground (at least along the proposed road right-of-way) with tags, paint, or flags. Fieldwork should be done during the spring freshet to aid in identifying the location of ephemeral watercourses.

The third step is to transfer information from the air photos onto accurate topographic base maps. The transferring can be done by hand or through stereo transfer methods.

Outputs

The outputs for a drainage plan project vary depending on the scope of the project. The basic product is a topographic map that identifies the location of watercourses, divides, and existing diversions (Figure 7).

Where a road is proposed, the location of any additional drainage struc-

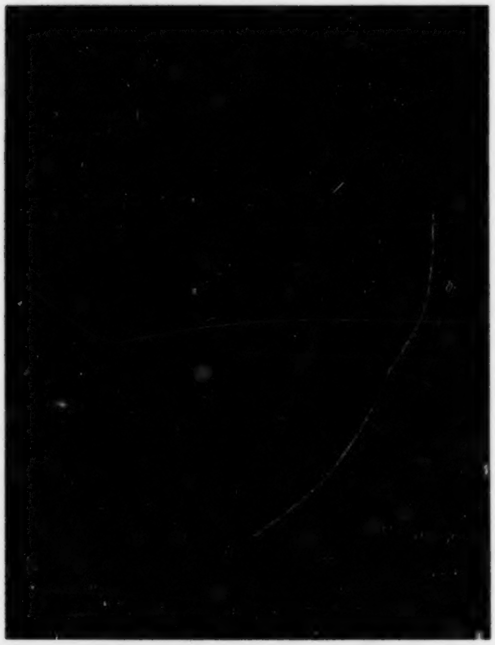

FIGURE 6 *The location and extent of existing drainage diversions must be determined before new road construction occurs downslope to avoid compounding problems (existing road – pink; proposed road – yellow; drainage divides – red)*

tures required to maintain natural drainage patterns should also be presented on the topographic base map. Where plans and profiles exist, the locations of additional drainage structures should be presented directly on the plans and profiles.

Outputs for a drainage plan can also include a hydrological assessment of proposed harvesting and road construction activities for small face unit drainages adjacent to high-value streams.

Where drainage plans are conducted in conjunction with road deactivation activities, divide and watercourse information should be included on deactivation maps.

INCORPORATING DRAINAGE PLANS INTO OPERATIONS

Two main challenges have been encountered by the authors and resource managers who have undertaken drainage plans:

1. initial incorporation of the drainage plan information into operations; and
2. retaining the information through maintenance, reconstruction, and deactivation activities.

The initial incorporation of drainage plan data into operations has proven difficult in a number of road projects where plans and profiles (RPS) have

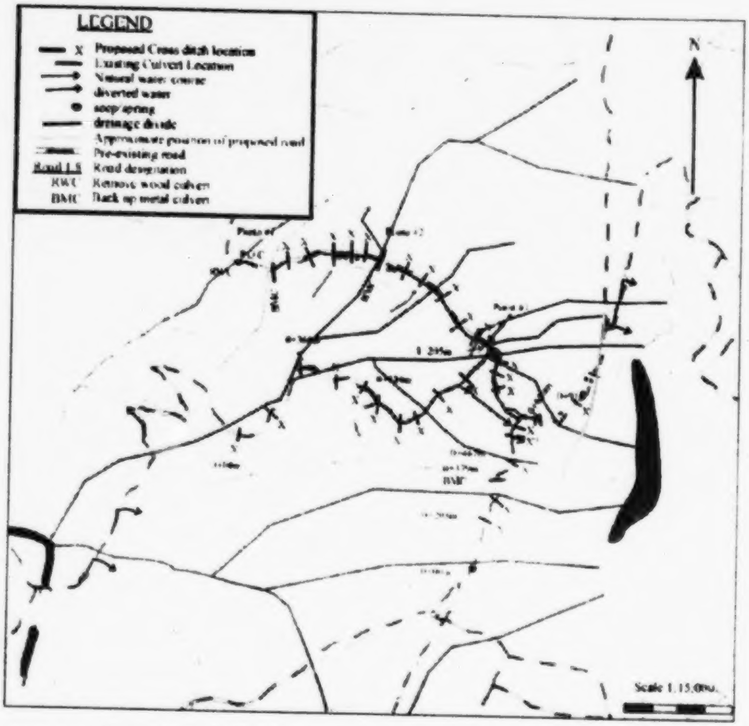
LEGEND
X Proposed Cross ditch location
Existing Culvert Location
Natural water course
diverted water
seep/spring
drainage divide
Approximate position of proposed road
Pre-existing road
Road 1.5 Road designation
RWC Remove wood culvert
BMC Back up metal culvert
N
Scale 1:15,000

FIGURE 7 *Example of drainage plan map.*

been produced independently of drainage plans. Confusion due to overlapping prescriptions occurs where operations managers and equipment operators are trying to work with the information from two separate plans and field markers.

The most difficult challenge over the long term has been in retaining the information from drainage plans through maintenance, reconstruction, and deactivation activities. This is primarily due to the lack of a formal process for archiving and retaining information from drainage plans—particularly if the drainage plan has been produced as a stand-alone product.

Some suggestions to address these challenges include:

1. developing company protocols for dealing with drainage plans;
2. placing signs along road segments where water diversions pose a risk to downslope resources. Signs also provide a non-verbal means to communicate the existence of a drainage plan in multiple user group situations; and
3. incorporating drainage plans into Ministry of Forests road design and road deactivation requirements.

RECOMMENDED APPLICATIONS OF DRAINAGE PLANS

A simple risk analysis approach (where Risk = Hazard × Consequence) is suggested for identifying, at a reconnaissance level, areas where drainage plans should be undertaken (Table 2). Drainage plans are recommended

TABLE 2 *Risk determination matrix (Moore 1994)*

	Hazard		
Consequence	**Low**	**Moderate**	**High**
Low	Low	Low	Moderate
Moderate	Low	Moderate	High
High	Moderate	High	Very High

where development or deactivation activities are proposed *on or above* areas with moderate or high likelihood of a slide (i.e., Class IV or V, or "P" or "U" terrain) that are situated above areas where the consequence of a slide occurring would be moderate to high (e.g., settlement or transportation corridors, community watershed intakes, high-value fisheries streams).

Drainage plans are also useful in identifying and maintaining slope drainage in "gentle-over-steep" terrain, which has been identified in the southern Interior landslide study as accounting for a significant number of slide events, as indicated by the following quote from Jordan (2001).

> An important category of landslides occurs some distance below roads, below a culvert or a point of accidental drainage discharge. In many of these cases, the road itself is on gently-sloping, low-hazard terrain, and the landslide occurs on steeper terrain below. This is known as the "gentle-over-steep" situation.

Drainage conditions in gentle-over-steep terrain generally consist of numerous small ephemeral streams in a dispersed or divergent drainage pattern (Figure 8). Road construction in this situation can easily concentrate and divert numerous unrecognized ephemeral watercourses. Concentrated and diverted water is discharged from the road prism and flows downslope onto steeper terrain, triggering slides due to the significant increase in surface and subsurface runoff (Grainger 2002).

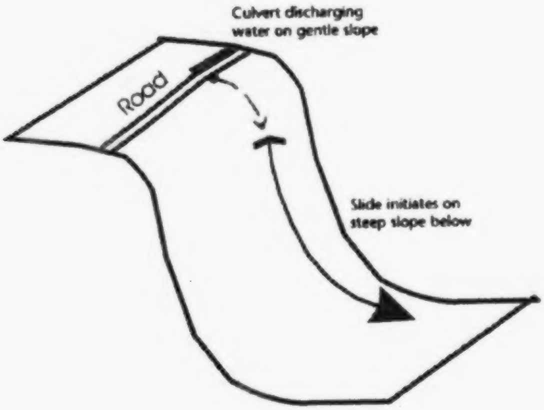
Culvert discharging water on gentle slope
Road
Slide initiates on steep slope below

FIGURE 8 *The "gentle-over-steep" situation.*

CONCLUSIONS

Where development or deactivation activities are proposed on or above high-risk terrain, the placement of drainage structures based on road gradient or preliminary road location surveys alone is often insufficient to maintain natural drainage patterns and slope stability. Drainage plans can be effective tools in reducing the occurrence of terrain instability events associated with resource road construction and deactivation.

Professionals undertaking drainage plans should use similar survey methods and provide standard outputs to reduce confusion surrounding the definition and utility of drainage plans.

Forest managers, planners, technicians, and professionals involved in resource road construction and deactivation need to take the first step in identifying where drainage plans should be undertaken and conducting drainage plans as part of road designs and deactivation prescriptions in high-risk terrain.

Due to the liability associated with prescribing drainage structures in high-risk situations, drainage plans should be completed and signed off by qualified registered professionals who have a comprehensive knowledge of air photo interpretation, slope hydrology, and terrain stability analysis.

ACKNOWLEDGEMENTS

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REFERENCES

Grainger, B. 2002. Terrain stability field assessments in "gentle-over-steep" terrain of the southern Interior of British Columbia. *In* Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proc. P. Jordan and J. Orban (editors). Nelson, B.C., May 23–25, 2001. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

Jordan, P. 2001. Regional incidence of landslides. In Proc. Watershed Assessment in the Southern Interior of British Columbia. D.A.A. Toews and S. Chatwin (editors). B.C. Min. For., Res. Br., Victoria, B.C. Work. Pap. 57/2001, pp. 237–47.

Moore, G. 1994. Resource road rehabilitation handbook: Planning and implementation guidelines (interim methods). B.C. Min. Environ., Lands and Parks, Victoria, B.C. Watershed Restoration Tech. Circ. No. 3.

Risk: A Tool for Communication between Foresters and Railroaders

B.J. NACHTIGAL, M.J. PORTER, AND T.R. KEEGAN

ABSTRACT

This paper proposes a qualitative methodology for assessing the risk to linear facilities from proposed upslope forestry developments (timber harvesting and road construction). The methodology is based on the Forest Practices Code of British Columbia guidelines for carrying out terrain stability field assessments, but modified to explicitly assess risks to downslope linear facilities. Examples illustrate how the methodology was used as a tool for communication between Canadian National Railway and forest managers. The authors postulate that the methodology discussed in this paper is applicable to manage the potential risk from forestry developments to other linear facilities such as pipelines, transmission facilities, and roads.

INTRODUCTION

Both forest managers and the operators of linear facilities are faced with the challenge of managing ground hazards such as rockfalls, debris flows, and surface erosion. Where forestry developments and linear facilities are close to each other, the activity of one can lead to an increased potential for ground hazards to affect the other, highlighting the importance of communication between stakeholders.

Risk management provides an effective framework for managing potential impacts from ground hazards and can be a valuable tool for facilitating communication and resolving potential land use conflict. This is illustrated through a description of the methodology developed by BGC Engineering Inc. and Canadian National Railway for evaluating risk to the railway from proposed forest road construction and timber harvesting activities. The methodology is based on a modification of current British Columbia forest industry risk assessment practices and conforms to Canadian Standards Association (CSA)'s *CAN/CSA Q850-97 Risk Management: Guidelines for Decision-Makers* (CSA 1997).

STAKEHOLDERS

Definition Stakeholders are defined as individuals, groups, or organizations that affect, are affected by, or believe they could be affected by, a decision or activity.

Decision-makers are also stakeholders (CSA 1997). Therefore, according to the above definition, operators of linear facilities are stakeholders when forestry activities are proposed or developed upslope of those facilities. This paper focuses on the interaction between forest managers responsible for forestry developments on Crown land and a specific stakeholder, Canadian National Railway.

British Columbia Forestry Managers

Managers responsible for timber harvesting on public lands in British Columbia are called upon to consider values in addition to commercial forestry. These non-timber resources include visual quality, archaeological sites, fish habitat, water quality and quantity, wildlife habitat, biodiversity, and terrain stability. In addition, the regulatory environment and land use policies in British Columbia have resulted in decreases in public provincial forest land available for commercial harvest. The effect of these factors in combination with past timber harvesting may result in timber harvesting activities occurring more frequently close to linear facilities.

Canadian National Railway

Canadian National Railway (CN) operates the Pacific North and South Corridors (Figure 1) for transporting passengers and freight between Edmonton, Alta., and the ports of Vancouver and Prince Rupert, B.C. Approximately 2500 km of mainline track is currently in operation within British Columbia. CN offers the shortest route to the midwestern United States for British Columbia forest products, which in 1999 accounted for close to 20% of CN's freight revenues, second only to grain and fertilizers (CN 2000).

Historically, railway engineers were driven to minimize both gradient and horizontal curvature. As a result, the Pacific North and South Corridor alignments follow valley bottoms near major watercourses for most of their length (Savigny et al. 1987; Keegan et al. 2000). Significant portions of these valley-bottom routes traverse terrain that is affected by geomorphic processes and ground hazards.

GROUND HAZARDS AND RISK MANAGEMENT

Ground Hazards

Foresters and railroaders face a number of different ground hazards. These can be categorized based on the broad distinction between landslides and erosion (Figure 2). Landslide hazards are further divided based on materials and slope movement types as defined by Cruden and Varnes (1996), and modified by Keegan et al. (2000). Timber harvesting and forest road–related factors in the British Columbia Interior that may contribute to landslide initiation are discussed below.

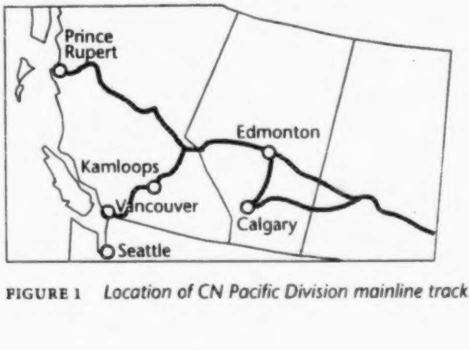


FIGURE 1 *Location of CN Pacific Division mainline tracks.*

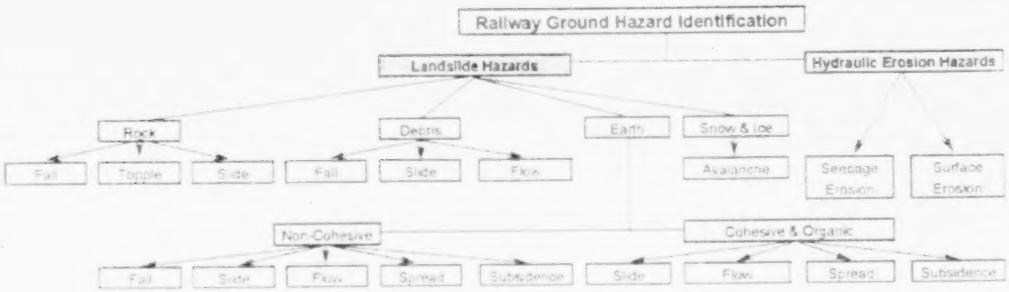

Railway Ground Hazard Identification
Landslide Hazards
Hydraulic Erosion Hazards
Rock
Debris
Earth
Snow & Ice
Fall
Topple
Slide
Fall
Slide
Flow
Avalanche
Seepage Erosion
Surface Erosion
Non-Cohesive
Cohesive & Organic
Fall
Slide
Flow
Spread
Subsidence
Slide
Flow
Spread
Subsidence

FIGURE 2 *Railway ground hazard classification (Keegan et al. 2000)*

Rises in the level of the phreatic surface may increase the frequency of landslides below harvested areas. Increased runoff may result in surface flow over marginally stable slopes below cutblocks, triggering landslides. For example, clearcuts tend to raise the level of the phreatic surface and increase water available for runoff by eliminating evapotranspiration of the forest cover. Also, increases in snow accumulation can occur. Research indicates that a 20–30% increase in snow accumulation can occur when closed-canopy forests are clearcut (Chapman 1999).

Factors associated with road construction that may contribute to landslide initiation include:

- removal of toe support from a slope by excavation of material;
- overloading slopes with sidecast fill material; and
- interception of surface and subsurface flows and redirecting them onto marginally stable slopes.

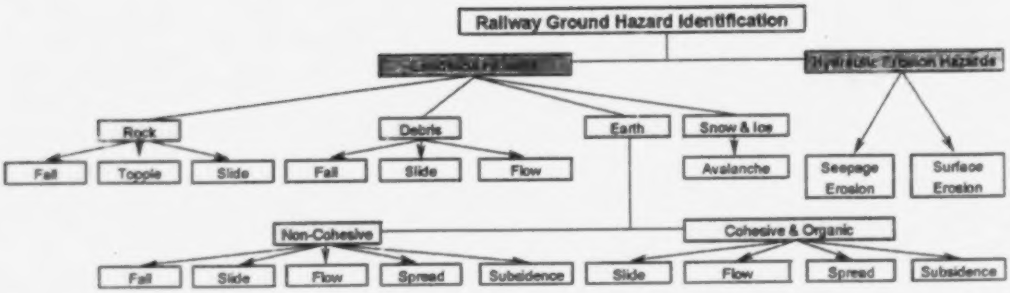
A critical topographic factor is the presence of gently sloping, forested plateaus above steep mountainsides subject to landslides. Forestry developments in seemingly innocuous terrain have caused diversion of water that has triggered landslides on steep slopes below (Jordan and Toews 1993).

Forestry activities can also increase the risk to downslope linear facilities from rockfall in the following ways. Timber harvesting may induce rockfall as logs are yarded over boulder-covered slopes or unstable bedrock slopes. The removal of forest cover can contribute to increased travel distances of natural rockfall events by eliminating the energy-absorbing capability of standing trees. Sidecasting boulders during road maintenance activities such as road surfacing and grading can create a rockfall hazard to linear facilities located below the roads being maintained.

Because the resources available to forest managers and railroaders for mitigating ground hazards are limited, a risk management system is required to identify and evaluate the hazards and establish priorities for monitoring and mitigation.

COMPONENTS OF A RISK MANAGEMENT SYSTEM

The object of risk management is to ensure that significant risks are identified and that appropriate action is taken to mitigate these risks (Keegan et al.


Railway Ground Hazard Identification
Hydraulic Erosion Hazards
Rock
Fall
Topple
Slide
Debris
Fall
Slide
Flow
Earth
Snow & Ice
Avalanche
Seepage Erosion
Surface Erosion
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Subsidence
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The object of risk management is to ensure that significant risks are identified and that appropriate action is taken to mitigate these risks (Keegan et al.

2000). The Canadian Standards Association's CAN/CSA Q850-97 *Risk Management: Guidelines for Decision-Makers* (CSA 1997) provides a framework for the development of a risk management system, as illustrated in Figure 3. The framework is comprised of six steps (Initiation, Preliminary Analysis, Risk Estimation, Risk Evaluation, Risk Control, and Action/Monitoring). Communication between stakeholders occurs at all six steps of the framework (Figure 3). Preliminary Analysis, Risk Estimation, and Risk Evaluation form the key components of a risk assessment, and are described in greater detail below.

"Preliminary Analysis" involves identifying, categorizing, and characterizing hazards. This is followed by the development of risk scenarios for the various hazard types identified. A risk scenario is a sequence of events with an associated frequency and consequence (CSA 1997).

"Risk Estimation" involves estimating both the likelihood of occurrence and consequences for the hazards identified to highlight risk scenarios that represent the greatest loss exposure. An estimate of the risk associated with a given scenario may be based on historical data, models, professional judgement, or a combination of methods. Practicality often dictates the use of a qualitative, as opposed to a quantitative, assessment (VanDine 1997).

"Risk Evaluation" is the process by which risks are examined in terms of costs and benefits. Evaluation is aimed at determining whether a given level of risk is acceptable. Pre-determined risk resolution matrices proposed by government agencies may aid in the evaluation and communication of risk. An example of a matrix proposed by the American Public Transit Association (APTA 1997) is illustrated in Table 1.

Where the level of risk is assessed to be unacceptable, the identification of "Risk Control" measures and implementation of mitigation and monitoring programs may be required.

Forest Practices Code and Risk Management

General Within the framework of the Forest Practices Code, the methods of identifying landslide hazards and estimating risks are detailed terrain stability mapping (DTSM) and terrain stability field assessments (TSFAS), respectively

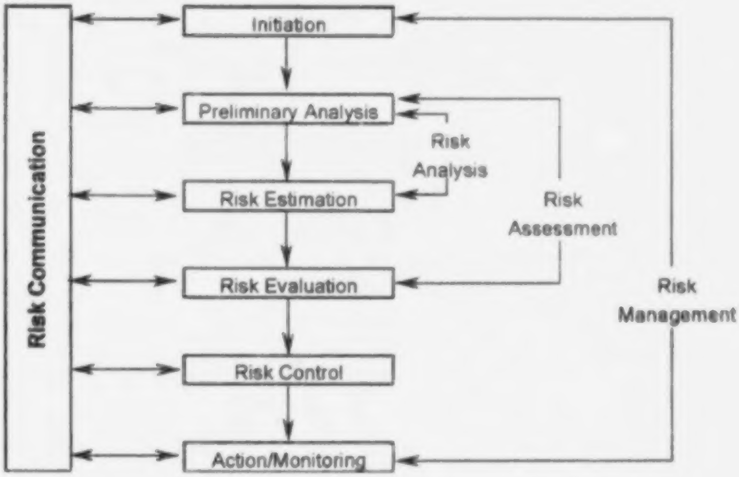

FIGURE 3 *Steps in the risk management decision-making process (after CSA 1997).*

TABLE 1 *Risk resolution matrix (modified from APTA 1997)*

	Severity			
Probability (Hazard)	**Catastrophic (High)** Death, major property damage, or system loss	**Critical (High)** Disability, significant property damage, or major system damage	**Marginal (Moderate)** Minor injury, minor property damage, minor system damage	**Negligible (Low)** Minor system impairment
Frequent (High) Likely to occur	Unacceptable	Unacceptable	Tolerable with mitigation	Tolerable with mitigation
Probable (High) Will occur several times in life of item	Unacceptable	Unacceptable	Tolerable with mitigation	Tolerable with mitigation
Occasional (Moderate) Likely to occur some time in life of item	Unacceptable	Tolerable with mitigation	Tolerable with mitigation	Tolerable
Remote (Low) Unlikely, but possible to occur in life of item	Tolerable with mitigation	Tolerable with mitigation	Tolerable with mitigation	Tolerable

(B.C. Ministry of Forests 1999). DTSM and TSFAS are discussed in a risk management context in the following sections.

Preliminary Analysis DTSM is similar to the hazard identification component of the preliminary analysis process outlined in Q850 (Figure 3). DTSM divides the landscape into polygons based on estimating the likelihood of landslide occurrence and other factors (British Columbia 2001). TSM rates the likelihood of landslide occurrence based on the following "hazard scenarios":

- timber harvesting is undertaken; or
- road construction using sidecast excavated material to construct the fill portion of the road prism (conventional techniques) is carried out.

The likelihood of landslide initiation is generally expressed in the qualitative terms Low, Moderate, or High (B.C. Ministry of Forests 1999). DTSM is not based on "risk scenarios" because the consequences that could result from landslide occurrence are not identified.

Based on the DTSM results, one of the following three courses of action can be taken:

1. The forestry development process can continue with no further terrain stability analysis;
2. The forestry development can be deferred as a risk control measure; or
3. A site-specific TSFA (risk estimation) is carried out before forestry development.

Forestry Risk Estimation

Rating the Likelihood of Landslide Occurrence In the context of the Forest Practices Code, landslide hazard is defined as the likelihood of landslide occurrence following timber harvesting or conventional road construction. Rating the landslide hazard is usually based on site characteristics, professional judgement, and the effect of logging or road construction on terrain near the forestry development being evaluated (historical data). In the absence of landslides related to forestry developments, landslide hazard estimates are also based on existing natural landslides in the area. Definitions for subjective hazard ratings (Low, Moderate, or High) are not included in the Forest Practices Code guideline for TSFAS (B.C. Ministry of Forests 1999). However, qualitative hazard ratings are provided in a guideline for determining inspection frequency on maintained and deactivated forest roads (Table 2). It is recommended that hazard ratings developed for a TSFA be based on site-specific terrain characteristics (Wise and VanDine 1999).

Rating the Potential Consequences of Landslides The potential downslope consequences from post timber harvesting and road construction landslides are also estimated based on site characteristics, professional judgement, and historical data. A field investigation and/or an office review of slope areas below proposed forestry developments to evaluate potential landslide initiation and runout zones are usually carried out. Based on that review, expected landslide size and length are estimated. In some cases, a consequence rating is applied based on the value of the downslope elements that could be impacted (Table 3). In the case of forestry roads, rehabilitation measures that could be required following a landslide must also be estimated (Province of British Columbia 2000).

Rating Landslide Risk Landslide risk is determined by combining hazard and consequence using the matrix shown in Table 4 (B.C. Ministry of Forests 1993), where:

Risk = Hazard × Consequence

Risk can be rated for a specific resource or value (Specific Risk), or it can be determined for all resources and values (Total Risk).

Risk Evaluation and Risk Control Guidance on the risk evaluation process (determination of what level of risk is acceptable) is provided in Forest

TABLE 2 *Sample hazard ratings (based on Table 14,* Forest Road Engineering Guidebook*)*

Hazard rating	Description
Low	The road is located on stable terrain with no landslide activity indicators. Normal road construction and logging practices will not significantly decrease terrain stability, except along road cuts. Soils are generally well compacted.
Moderate	The road is located on stable terrain with no landslide activity indicators. Minor stability problems may develop. Erosion is limited to small-scale slumping and ravelling. Cut-and-fill slope erosion and surface erosion are generally shallow.
High	The road is located on terrain with visible or suspected evidence of landslides or mass wasting. It is not limited to any particular sideslope, although the steeper the ground, the greater the potential for avalanches and debris torrents. Soils may also be highly erodible.

Note: Areas that are subject to high-frequency intense rainstorms (such as the west and north coast of Vancouver Island, the west coast of the Queen Charlotte Islands, the Mid-Coast, and the Mission-Hope areas) should be given special recognition and may have their hazard ratings increased to allow for this.

TABLE 3 *Consequence ratings (based on Table 4, Chapter 8,* MOF Engineering Manual *[B.C. Ministry of Forests 1993])*

On-site downslope/ downstream values adjacent to road alignment	Consequence (or severity) ratings—Forecast the consequence or severity of the damage or loss to a specific value should erosion and sedimentation occur		
	Low	Moderate	High
Forest site productivity	Areas not rated as moderate or high	Areas having moderate potential to grow merchantable timber	Areas having high potential to grow merchantable timber which, if damaged, would have serious long-term effects on regeneration
Human life, property, roads, and railways	Areas that are uninhabited and undeveloped, or occasionally inhabited territory and cultivated farm land	N/A	Areas having rural development, domestic dwellings, industrial development, highways, and railways
Utilities	Areas with no utilities	N/A	Areas having electric transmission towers, gas and oil lines, or fibre optic cable

TABLE 4 *Risk ratings (based on Table 2, Chapter 8,* MOF Engineering Manual *[B.C. Ministry of Forests 1993])*

Consequence rating	Hazard rating		
	High	Moderate	Low
High	Very high risk	High risk	Moderate risk
Moderate	High risk	Moderate risk	Low risk
Low	Moderate risk	Low risk	Low risk

Practices Code regulations and guidelines. Some risk control measures are legislated based on estimates of the likelihood of landslide occurrence (e.g., requiring that a particular harvesting system not be used in areas identified as having a moderate or high hazard [Province of British Columbia 1998]).

In areas where risk is determined to be unacceptable by the forestry manager, site-specific actions (risk controls) to reduce the likelihood of landslides are incorporated in the design of the forestry development. Those measures are prescribed as a part of the TSFA (B.C. Ministry of Forests 1999). Examples of risk control measures for forest roads include:

- increasing the frequency of inspections and road maintenance;
- using angular rock as fill material;
- relocating road segments; or
- deactivating roads (shortening the life of roads) in areas where long-term access is not required.

Risk Communication The results of a TSFA are communicated to the forest company (licensee) by written report. Generally, regulations do not require that a TSFA report be submitted to the B.C. Ministry of Forests (MOF). However, risk control measures recommended in a TSFA report are communicated to the MOF as part of the road or cutblock design documentation submitted to that agency by licensees.

CN Risk Management Practice

CN has developed and continues to refine a risk management system for ground hazards that follows the framework outlined in Q850 (CSA 1997). The objective of the system is to minimize the likelihood of train derailment, injury or loss of life, environmental damage, and track outage through the most efficient allocation of hazard management funds.

CN generally identifies ground hazards through geotechnical field inspections, incident and condition reporting from operating personnel, air photo interpretation, and aerial reconnaissance of drainage conditions and anthropogenic activity. Categorizing and characterizing the hazards according to Figure 2 provides a significant advantage in that the hazards within each category tend to have similar risk scenarios.

CN's long history of dealing with ground hazards has lead to the recognition that risk scenarios involving rockfalls, debris flows, earth slides in silt and fine sand, river erosion, hydraulic erosion attributed to beaver activity, and rapid runoff are most critical. These scenarios occur frequently without a long warning period and often have severe consequences. Systems for managing rockfall- (Canadian National Rockfall Hazard and Risk Assessment [CNRHRA]) (Abbott et al. 1998a, 1998b) and beaver- (Beaver Activity Hazard Assessment [BAHA]) related hazards have already been developed. Sections of track are assigned a numerical score for each risk scenario. The hazard score assists in assigning priorities for inspection, mitigation, and monitoring.

CN Forestry Risk Assessment

The main objective of the CN Forestry Risk Assessment (CNFRA) methodology is to identify and rate the potential risk to the CN grade resulting from ground hazards that could be triggered by proposed forestry developments above the grade. The CNFRA process consists of three main components that:

- identify and categorize hazards and potential triggers (Preliminary Analysis);
- assess hazard frequency, magnitude, likelihood, and consequence of impact under proposed design (Risk Estimation); and
- determine if the risk is acceptable (Risk Evaluation).

Ideally, each component of the CNFRA can use the information gathered during terrain stability mapping and field assessment work conducted on behalf of the forest managers where required under the Forest Practices Code.

Preliminary Analysis The first component of the CNFRA is to conduct a preliminary analysis to identify proposed forestry developments that have the potential to impact the CN grade. The preliminary analyses rely on communication with the MOF and licensees. Communication with the MOF consists of informing MOF district managers of the perception of risk to the CN grade where proposed forestry developments are located:

- upslope and within 1 km (horizontal distance) of the CN railway; and
- in valleys or gullies upstream of CN culverts and upstream of bridges supported by piers, trestles, or abutments that are within the wetted perimeter of rivers or creeks flowing out of those valleys.

Communication with licensees and the MOF's Small Business Forest Enterprise Program relies on public review and comment (Province of British Columbia 2001). Forest development plans are reviewed at public meetings and comments are provided where proposed forestry developments meet the above criteria. In some cases, site-specific field assessments of proposed developments are carried out using the following methodology.

Risk Estimation A qualitative risk assessment methodology is used to estimate the potential risk to the CN grade originating from each proposed cutblock, road, and designated trail. The terminology used for risk estimation has been adapted from three main sources: the British Columbia Resources Inventory Committee (RIC) (1996), Fell (1994), and the Transport Safety Management System Guide (Transport Canada 2000). The risk assessment terminology used in this methodology follows.

Definitions For the purpose of the CNFRA, risk is defined as:

- Risk = Likelihood of a Hazard Occurring × Consequence, where:
- Hazard is defined as condition and/or circumstance that increases the likelihood and/or severity of loss; and
- Consequence is a combination of likelihood of an event impacting the CN grade, and the Severity of Impact, should the hazardous event occur.

Potential hazards, likelihood of hazard occurrence ratings, and consequences are discussed in the following sections.

Hazard Classification and Ratings The ground hazards considered in the CNFRA are landslides or changes in hydrogeologic conditions resulting from timber harvesting or conventional road construction.

In the CNFRA, landslide hazards are described based on their classification, and on estimates of their potential magnitude. Classification is a description of material and slope-movement type (e.g., debris slide or rockfall) according to Figure 2. Magnitude refers to the volume of displaced material involved in landslide hazards. Potential landslide hazard classification and estimates of their magnitude are based on professional judgement, the characteristics of the terrain, classification and assessment of existing landslides (historical data), and site-specific information obtained during field traverses.

Changes in hydrologic or hydrogeologic conditions resulting from timber harvesting or conventional road construction may result in surface water concentration at the CN grade or increased subsurface seepage towards the CN grade. In the CNFRA, water concentration is defined as increased surface flow, subsurface flow, and flow in existing creeks. A qualitative assessment of the magnitude of the hazard is based on observed surface water conditions, inferred subsurface water conditions, and the size of the area that will be altered by timber harvesting or road construction relative to the total area of the slope above the rail grade.

The likelihood of a hazardous event occurring is rated qualitatively using the definitions outlined in Table 5.

Consequence Classification and Ratings Water concentration and landslide hazards resulting from proposed forestry developments could lead to Consequences at the CN grade. The Consequence Rating depends on the likelihood of the hazardous event affecting the CN grade, and the anticipated Severity of the Impact.

Consequence is rated using the matrix shown in Table 6. For example, an

TABLE 5 *CNFRA likelihood of hazard occurrence ratings*

Rating	Definition
High	Likely to occur frequently or several times following timber harvesting or conventional road construction. (Evidence of recent or ongoing events were observed)
Moderate	Likely to occur sometime following timber harvesting or conventional road construction. (Indicators that an event could occur or has occurred in the past were observed)
Low	Unlikely, but possible to occur following timber harvesting or conventional road construction. (Areas where a High or Moderate rating does not apply)

TABLE 6 *CNFRA consequence ratings*

	Examples of anticipated severity of impact to the railway		
Likelihood of impact	High Mainline disruption for > 6 hrs; or > $100K damage	Moderate Mainline disruption for 1–6 hrs; or > $10K damage	Low Mainline disruption for < 1 hr; or < $10K damage
High	High	High	Moderate
Moderate	High	Moderate	Low
Low	Moderate	Low	Low
Negligible	Negligible	Negligible	Negligible

event assessed as a low likelihood to impact the railway, but with a high Severity of Impact, yields a Moderate Consequence rating.

For landslides, likelihood of impact is rated subjectively based on the proximity of the hazard to the CN grade and an assessment of whether the grade is located within the initiation, transport, or deposition zone of the potential slide. An evaluation of existing landslides, including landslide classification, slope morphology, surficial materials, surface and subsurface drainage conditions, inferences of factors that may have contributed to landslide initiation, and runout distance, assist with making this assessment.

The Severity of Impact is a function of several factors, including:

- the amount of time available to react to the hazardous condition (i.e., will a potential landslide move at a rate of a metre per year or metre per second);
- the proximity to CN's maintenance resources (i.e., how remote is the site); and
- the type (i.e., rock, debris, earth) and volume of material that could be deposited on the CN grade. Rock and debris are more likely to derail trains, as are larger volumes of material. Large volumes of material also take longer to clear from the tracks, resulting in greater service disruption.

For surface water concentration and increased subsurface seepage, the consequence ratings are based on an assessment of the potential to initiate landslides between the proposed forestry activity and the rail grade, and on the presence and condition of culverts along the rail grade.

For increased flow in creeks, the consequence ratings are based on the potential for triggering channelized debris flows and the capacity of the hydraulic structures along the rail grade to pass increased flow or debris flow events.

Risk Evaluation—The Risk Resolution Matrix Risk to the CN grade is evaluated using the resolution matrix presented in Table 7. The only element at risk considered in the CNFRA is the CN Rail grade. Other resource elements such as visual quality, recreation, fish, wildlife, and forest site productivity are not considered.

The risk associated with each potential hazard is evaluated as Very High, High, Moderate, Low, or Negligible. Modification to the proposed timber harvesting area or road design is generally recommended where the risk is evaluated as being Moderate to Very High.

Risk Communication and Risk Control The results of the risk estimation phase discussed previously contribute critical information to the stakeholders. Using a common language (risk, hazard, likelihood of occurrence, and consequence) to convey this new information can significantly improve the level of knowledge of the stakeholders, and change their perceptions of the risks. It is beneficial to discuss the preliminary results of field assessments, preferably during meetings between stakeholder representatives.

Dialogue builds trust between decision-makers and other stakeholders. If stakeholders trust the risk estimation process, the conclusions and any decisions (risk controls) resulting from any conclusions stand a much better chance of being accepted (CSA 1997).

Common risk control measures that can reduce the likelihood of hazard occurrence or potential consequences of those hazards include modifying cutblock boundary locations, where feasible from a timber harvesting point of view; prescribing three-quarters or full bench road cuts or more extensive road/trail deactivation measures than might otherwise be required; or decreasing culvert spacing.

Where culverts along the CN grade have been damaged, or where rock drains were installed during original construction, culverts can be repaired or installed before timber harvesting or road construction.

CONCLUSIONS

Forest managers and the operators of linear facilities are both faced with the challenge of managing ground hazards. Where forestry developments and linear facilities are close to each other, the activity of one can lead to an increased potential for ground hazards to affect the other.

TABLE 7 *CNFRA railway-specific risk resolution matrix*

Probability of hazard occurrence	Consequence			
	High	Moderate	Low	Negligible
High	Very high risk	High risk	Moderate risk	Low risk
Moderate	High risk	Moderate risk	Low risk	Negligible risk
Low	Moderate risk	Low risk	Low risk	Negligible risk

Risk management provides an effective framework for managing the potential impacts from ground hazards and can be a valuable tool for facilitating communication between stakeholders. Communication builds trust between decision-makers and other stakeholders. If there is trust between stakeholders, decisions stand a much better chance of being accepted.

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REFERENCES

Abbott, B., I. Bruce, W. Savigny, T. Keegan, and F. Oboni. 1998a. A methodology for the assessment of rockfall hazard and risk along linear transportation corridors. *In* 8th Congress of the International Association for Engineering Geology and the Environment, Vol II: 1195–1200. Balkema, Rotterdam, Netherlands.

———. 1998b. Application of a new methodology for the management of rockfall risk along a railway. *In* 8th Congress of the International Association for Engineering Geology and the Environment, Vol II: 1201–8. Balkema, Rotterdam, Netherlands.

American Public Transit Association (APTA). 1997. Manual for the development of system safety program plans for commuter railroads. Washington, D.C.

B.C. Ministry of Forests. 1993. Engineering manual. Chapter 8. Victoria, B.C.

———. 1999. Forest road engineering guidebook. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

———. 1999. Mapping and assessing terrain stability guidebook. 2nd ed. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

Canadian National Railway Company (CN). 2000. Investor fact book. Canadian National Railway Company, Montreal, Que. Digital file available at http://www.cn.ca/PDF/cnfinal.pdf

Canadian Standards Association (CSA). 1997. Risk management: guidelines for decision-makers, CAN/CSA-Q850-97, 1997. Canadian Standards Association, Etobicoke, Ont.

Chapman, A. 1999. Introduction to forest hydrology. *In* Module 5: Forest soils and hydrology. Inst. For. Eng. B.C., Univ. B.C., Vancouver, B.C.

Cruden, D.M. and D.J. Varnes. 1996. Landslide types and processes. *In* Landslides: Investigation and mitigation. Transportation Res. Board, Natl. Acad. Press, Washington, D.C. Spec. Rep. 247. A.K. Turner and R.L. Schuster, (editors). Chapter 3: 36–71.

Fell, R. 1994. Landslide risk assessment and acceptable risk. Can. Geotech. J. 31:261–72.

Jordan, P. and D. Toews. 1993. Terrain and hydrologic factors influencing logging-related landslides in south-eastern British Columbia. Paper presented at Can. Quaternary Assoc., Biennial Meet., Apr. 18–21, 1993, Victoria, B.C.

Keegan, T., B. Abbott, and M. Ruel. 2000. A risk management framework for ground hazards along Canadian National Railways. *In* Proc. 53rd Can. Geotechnical Conf., Montreal, Que., Oct. 2000.

Province of British Columbia. 1998. Timber harvesting practices regulation. *Forest Practices Code of British Columbia Act.* Consolidated to Dec. 23, 1998.

———. 2000. Forest road regulation. *Forest Practices Code of British Columbia Act.* Consolidated to Nov. 23, 2000.

———. 2001. Operational planning regulation. *Forest Practices Code of British Columbia Act.* Consolidated to Mar. 30, 2001.

Resources Inventory Committee. 1996. Terrain stability mapping in British Columbia. B.C. Resources Inventory Committee, Victoria, B.C. Computer file available at http://srmwww.gov.bc.ca/risc/pubs/earthsci/terrain2/index.htm.

Savigny, W., M. Klassen, and W. Jubian. 1987. Geotechnical practice in transportation–Railroads. Proc. 40th Can. Geotechnical Conf., Montreal, Que., May 1987.

Transport Canada. 2000. Railway safety management systems guide (Draft). Transport Canada, Ottawa, Ont. Digital file available at http://www.tc.gc.ca/railway/publications/smsguide.htm.

VanDine, D.F. 1997. Landslide hazard and risk assessments for small projects, preliminary studies and emergency response. *In* Landslide risk assessment. D.M. Cruden and R. Fell (editors). Balkema, Rotterdam, Netherlands, pp. 365–9.

Wise, M.P. and D.F. VanDine. 1999. Landslide risk assessment associated with forest roads. Discussion paper prepared for Risk management committee, MOF, forest industry forest engineering steering committee. B.C. Min. For., Victoria, B.C. Unpublished report.

Risk Assessment Procedure for Proposed Resource Development Activities above Alluvial and Debris Torrent Fans

DWAIN BOYER

ABSTRACT

Alluvial and debris torrent fans are common landforms in the Kootenay Region of British Columbia. Many of the fans are relic features, products of the last deglaciation period. However, many remain active or potentially active. Rapidly melting snow, heavy rains, channel blockages, and/or landslides can result in avulsions and/or debris torrent or debris floods on these fans. Private and public lands, infrastructure, and people occupying the fans are at risk of being damaged during these extreme events. For the most part, these events occur naturally. However, resource extraction activities, such as timber harvesting and mining, can increase the risk by increasing peak flows and/or the number of landslides. There are also emerging concerns about climate change due to global warming. Predictions include the possibility of warmer temperatures and more extreme storm events. Over the last few years, the B.C. Ministry of Water, Land and Air Protection (formerly the Ministry of Environment, Land and Parks) has mapped many of these fan areas so that forest licensees, woodlot owners, and mining companies can be aware of these risks when planning development in watersheds. The object of this paper is to present a procedure for assessing this risk.

PURPOSE

There are many alluvial and colluvial fans along populated valley bottoms in the steep mountainous terrain of the southeast corner of British Columbia. During periods of high runoff, channels can shift (Figures 1 and 2) and debris flows can reach valley bottoms (Figure 3) with devastating effects on people and property. Timber harvesting and road construction in watershed areas above these fans can increase the frequency and magnitude of floods and debris flows on the fans. Terrain stability field assessments, required by the Forest Practices Code (FPC), can reduce risks associated with individual road segments and cutblocks in areas where they are required. However, except in community watersheds and some high-value fishery streams, watershed-scale risk assessment procedures are not required. In addition, there is no recognized standard procedure for the preparation of a watershed-scale risk assessment report.

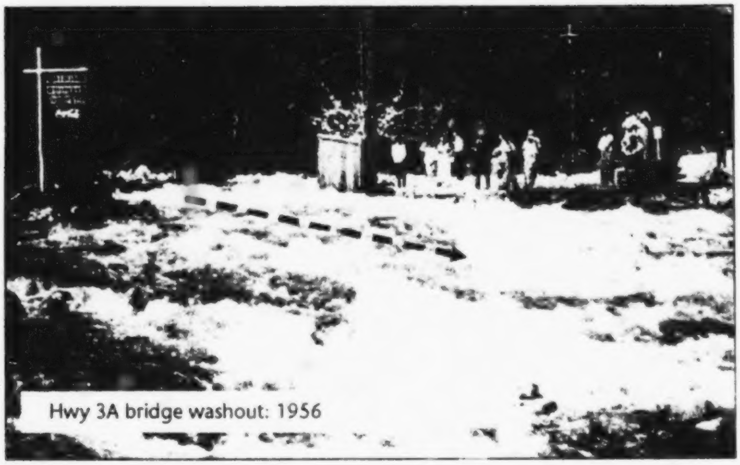

Hwy 3A bridge washout: 1956

FIGURE 1 *Duhamel Creek bridge: 1956.*

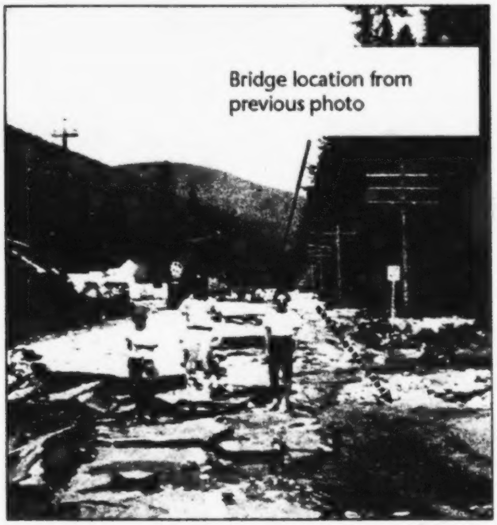

Bridge location from previous photo

FIGURE 2 *Duhamel Creek fan: 1956.*

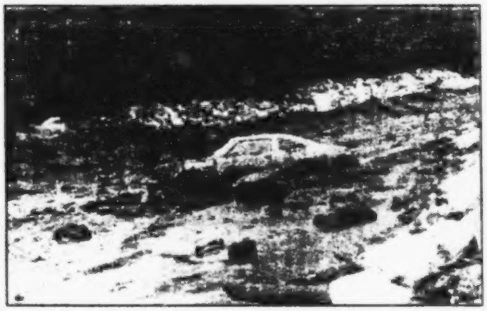


FIGURE 3 *Birchland Creek fan debris flood: 1982.*

In this paper, "alluvial" refers to fans built up from sediment carried by flood waters, while "colluvial" fans are formed mainly by debris flows, a type of mass movement also commonly called debris torrents.

The purpose of this document is to propose a procedure to assess the additional risks associated with resource development activities to people and property situated on these fans.

EXISTING RISK ASSESSMENT REPORTS RELATED TO PUBLIC SAFETY

This section identifies existing reports and procedures that deal with resource development risk assessments.

Interior Watershed Assessment Procedure

The Forest Practices Code (FPC) *Watershed Assessment Procedure Guidebook* (WAPG) (B.C. Ministry of Forests 1999) is the only legislated requirement for a watershed-scale risk assessment dealing with public safety on fans. Section 14 (1) of the Operational Planning Regulation (OPR) states that a person proposing a forest development plan in a community watershed area must first carry out a watershed assessment. Section 14 (2) of the OPR states that watershed assessment for community watersheds in the Interior of British Columbia must be carried out in accordance with the WAPG or equivalent. The guidebook states that the reporting hydrologists and the Watershed Assessment Committee must identify and assess downstream flooding and debris flow risk. The guidebook, however, was written primarily to assess risks to community drinking water supplies. The guidebook does not provide direction on how to assess risks to people and property on a fan at the outlet of the watershed.

Terrain Stability Field Assessments

Section 2.5 of the FPC Forest Road Regulation requires a person proposing to construct roads in areas with moderate or high likelihood of landslide activity to carry out terrain stability field assessments (TSFAS). Section 16 of the OPR states that TSFA reports are required for any cutblock proposed in areas with moderate to high likelihood of landslides in community watersheds. Section 17 of the OPR requires TSFA reports for all cutblocks in areas with a high likelihood of landslides. The TSFA reports provide risk assessments for cutblocks and/or road segments in some areas of a watershed where new development or road deactivation work is proposed. Cumulative and off-site effects of roads and harvesting in watersheds are often not considered.

Perry Ridge Risk Assessment Report

An overview risk assessment report was prepared for the Perry Ridge area in the Slocan Valley (Boyer et al. 1999; VanDine et al. 1999). This is an example of a strategic-level risk assessment that is not required by regulation. After identifying geologic and hydrologic hazards in the study area, the report provided an assessment of the existing risks posed to life and limb, property, and water supply. Anticipated risks associated with proposed road building and logging on Crown land were then determined. Several streams discharge onto populated alluvial and colluvial fans at the base of the ridge. Several map products, not usually available for forest development planning, were used in the study. These included geological hazard maps for the private land on the valley bottom, stream channel surveys, and a total-chance logging plan. The report provided strategic-level advice on where higher-risk areas exist and where more detailed professional review is required, and suggests measures to reduce risks.

Ministry of Water, Land and Air Protection

Under Section 82 of the *Land Title Act*, a person proposing to subdivide property in areas subject to flooding must first obtain consent from the Ministry of Water, Land and Air Protection (WLAP). WLAP also provides local governments with floodplain maps for bylaws, and assists with the construction of flood and debris torrent protection works on floodplains and active fans. These regulatory requirements sometimes result in the developer hiring an engineer/geoscientist to prepare risk assessment reports for fan areas. Some of these reports provide useful information such as the predominant hazard type, the frequency of events, and consequences.

Local Governments

Local governments have the mandate to control and direct land use. Floodplain bylaws, development areas, and building permits are used to direct appropriate uses of hazardous lands. Risk assessments reports and maps may provide information on predominant hazard type, frequency of events, and consequences.

WHERE SHOULD RISK ASSESSMENT REPORTS BE REQUIRED?

In some areas of the province, relic paraglacial fans pose a very low risk to people and property on the fan. These fans have an incised, unobstructed, single channel from the apex to the toe of the fan with channel capacity to convey major floods (1-in-200-year flood discharge) without avulsing or overtopping. Debris flows do not reach the fan under the present-day condition. The chance of human-made changes "re-activating" one of these relic fans is very low. On this type of fan, watershed risk assessments are not warranted.

However, most active or potentially active fans in the Kootenays are not of this paraglacial type. Most fans do not have a "bullet-proof" channel, able to convey major floods with attendant timber debris, ice, and bedload. Many fans in the region have been constructed, at least partially, by debris flow. In the steep watersheds, road construction and timber removal can renew landslide vigour and transform an inactive relic fan into an active fan. Consequently, risk assessments should be required above most high-consequence fans in the region.

Alluvial and/or debris torrent fan risk assessment reports should be required where watershed development activities, such as forest harvesting and mineral exploration, have the potential to significantly increase the risk of damage to people and property on valley-bottom fans.

In 1998, WLAP's Kootenay Regional office in Nelson, B.C., began compiling an inventory of areas at risk on the valley bottoms. Under contract with WLAP, Klohn Crippen Consultants Ltd. (1998) identified potentially active alluvial and debris torrent fans along the main settlement and travel corridors for the Kootenay Region. Some 650 fans were identified using air photographs and existing reports. Of these, 50 fans were inspected on the ground by Klohn Crippen staff to delineate active fan boundaries. The 600 fans that were not field verified were labelled "potentially active alluvial and/or debris flow fans" and were identified as dots on a map. This information was combined with WLAP's pre-existing active fan inventory.

Since this initial inventory, ongoing fieldwork by WLAP staff and others has resulted in the mapping of approximately 70 additional fan polygons. The Regional District of Central Kootenay (RDCK) has a project in progress to delineate all geological boundaries for all known potential fans in its region. The fan polygons are being created using air photographs. Consequently, the dominant hazard type and degree of geologic activity are not confirmed on these fans. A project is in progress to make all WLAP and RDCK identified polygons available on a Web site.

Using these polygons, forest licensees and others can determine where their activities have the potential to increase risk to people and property.

DETERMINATION OF DOMINANT HAZARD ON THE FANS

The assessment procedure will vary depending on the predominant hazard affecting the fan area. The primary concern in watersheds above alluvial fans is a possible increase in the magnitude and frequency of peak flows at the fan apex and below. Consequently, for alluvial fans, the proposed risk assessment procedure focuses on the primary activity that tends to increase the risk of flooding (e.g., the rate of tree removal and road building). Conversely, for areas above a colluvial fan, the primary concern is with landslide initiation, and the assessment procedure focuses on the assessment of roads and tree removal on or below steep unstable terrain.

A field review by a qualified professional is usually required to determine the dominant hazard type on a fan. Existing studies and/or mapping mentioned in the previous section may provide this information or be useful to help make the determination. Melton's ruggedness number (Melton 1965; Jackson et al. 1987; Boyer 1999) can be used as an initial assessment before going to the field. Generally, for larger watersheds with larger, flatter fans (third-order streams and higher), the main concern on the fan is flooding. Smaller, steeper watersheds with smaller, steeper fans usually have fans that have been partially or mostly constructed from debris flow events. On these fans the main concern is the volume and runout distances for debris flow events.

Jackson et al. (1987) describe a methodology for the determination of the dominant hazard on a fan (Figure 4). A fan is classified as an alluvial fan if all the answers to the questions in Step 1 of Figure 4 are negative. The hazards on an active alluvial fan include overbank flooding and avulsion. Positive answers to any of the questions in Step 1 of the flowchart indicate that the fan was at least partly constructed by debris flows.

RISK ASSESSMENT PROCEDURE FOR AREAS ABOVE ALLUVIAL FANS

Map Sub-Basins and H60 Lines

The first step is to delineate watershed boundaries above the apex of the fan on a suitably scaled map (usually between 1:10 000 and 1:20 000). Sub-basin drainage boundaries and H60 lines are then mapped (B.C. Ministry of Forests 1999). Watershed and sub-basin equivalent clearcut areas (ECAS) are calculated using procedure described in the *Watershed Assessment Procedure Guidebook* for existing conditions and proposed development scenario.

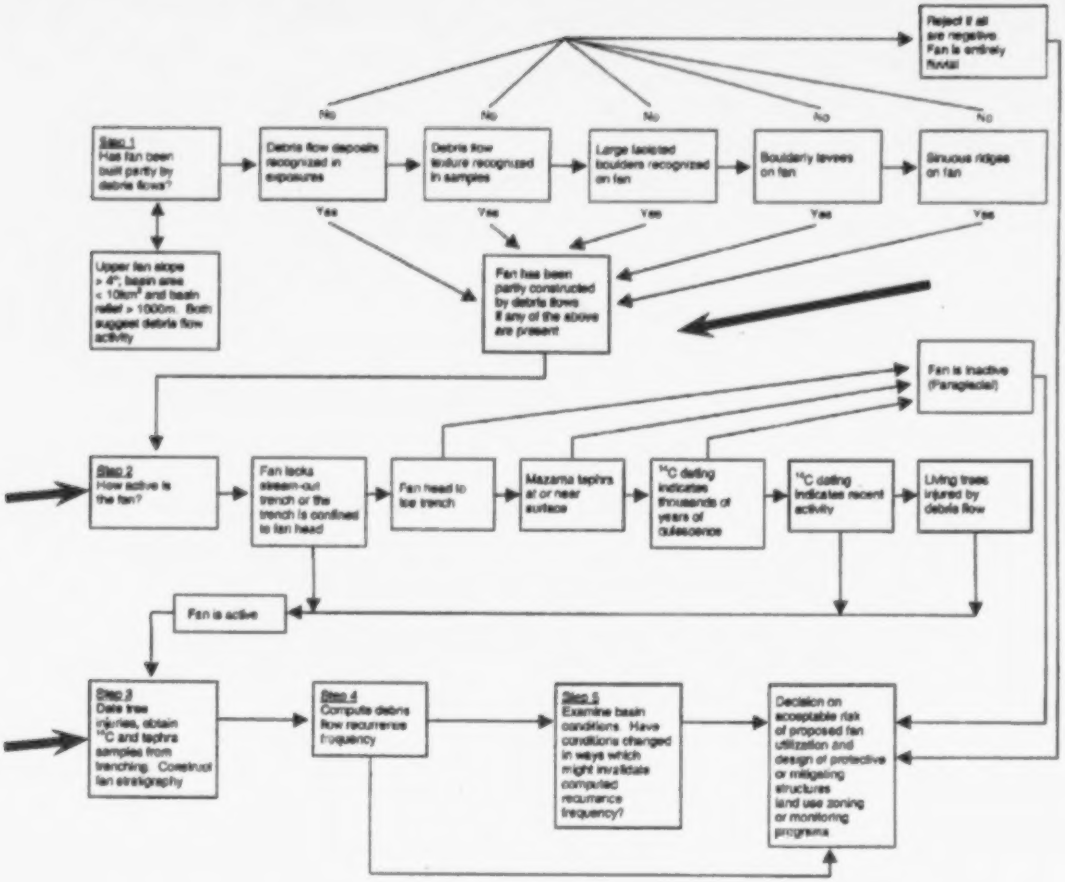

Reject if all are negative Fan is entirely fluvial
No
No
No
No
No
Step 1 Has fan been built partly by debris flows?
Debris flow deposits recognized in exposures
Debris flow texture recognized in samples
Large isolated boulders recognized on fan
Boulderly levees on fan
Sinuous ridges on fan
Yes
Yes
Yes
Yes
Yes
Upper fan slope > 4°, basin area < 10km² and basin relief > 1000m. Both suggest debris flow activity
Fan has been partly constructed by debris flows if any of the above are present
Fan is inactive (Paraglacial)
Step 2 How active is the fan?
Fan lacks stream-cut trench or the trench is confined to fan head
Fan head to toe trench
Mazama tephra at or near surface
¹⁴C dating indicates thousands of years of quiescence
¹⁴C dating indicates recent activity
Living trees injured by debris flow
Fan is active
Step 3 Date tree injuries, obtain ¹⁴C and tephra samples from trenching. Construct fan stratigraphy
Step 4 Compute debris flow recurrence frequency
Step 5 Examine basin conditions. Have conditions changed in ways which might invalidate computed recurrence frequency?
Decision on acceptable risk of proposed fan utilization and design of protective or mitigating structures land use zoning or monitoring programs

FIGURE 4 *A flow diagram summarizing debris flow hazard evaluation methodology. (Source: Jackson 1987.)*

Hazard Rating

A hazard rating is then assigned for the watershed and sub-basins using Table 1. The hazard ratings are based on ECA calculations. Several other factors, such as road density and the spatial distribution of disturbances, obviously have effects on the runoff hydrograph. However, it is assumed that these effects are sufficiently accounted for in the ECA calculation. With the continued advances in computing power, digital terrain mapping, and remote sensing, engineers and scientists will soon be able to model development proposals on virtual representations of watersheds (Whitaker et al. 2001) and routinely make decisions on risk. Until then, using ECA values is judged to be an adequate representation of the level of disturbance in the watershed.

Hazard ratings can be assigned using more detailed and sophisticated methods. Threshold ECA values presented in Table 1 were determined through a review of paired watershed studies and guideline documents used in southern British Columbia.

TABLE 1 *Avulsion hazard rating*

ECA level	Avulsion hazard rating
< 15%	Low
15–25%	Medium
> 25%	High

Consequence ratings are assigned using Table 2. The table assigns a consequence rating based on housing density. This approach was taken for several reasons:

Consequence Rating

1. Some local governments have established rural land use bylaws that set lot sizes and building densities. These are an expression of local desire for housing density and should remain static for the mid to long term.
2. As mentioned previously, WLAP has mapped many of the populated fans in the region. This, along with the administration of floodplain management programs (subdivision approvals by the provincial government and floodplain bylaws by the local governments), will tend to keep lot sizes at existing levels in high-hazard areas.
3. Fan areas have been identified for local governments, so that in areas that have building bylaws, building inspectors do not approve new building construction without due consideration for the flood and/or debris flow hazards.
4. Most local governments have bylaws that restrict the number of principal dwellings to one per lot.
5. Highways, secondary roads, railways, and utilities are common features on the fans in the valley bottoms.

If a hospital, school, or other such important infrastructure exists on a fan, then the consequence rating should automatically be raised to High.

Risk Rating

Hazards and consequences are combined to establish a risk rating using Table 3. If the risk rating for the entire watershed and all sub-basins is Low, then the development proposal should be allowed to proceed, subject to normal Forest Practices Code requirements.

If the risk rating for the entire watershed is Low but one or more of the sub-basins has a High hazard rating, then an assessment should be completed for the mainstream channel below the confluence of the sub-basin(s). The assessment, undertaken by a stream channel specialist, determines if increased peak flows emerging from the sub-basin(s) will increase movement of bedload and woody debris and/or increase bank erosion in the main channel. If main channel disturbance is anticipated, the professional should then assess the risk of the destabilizing effect reaching the fan and increasing the

TABLE 2 *Consequence rating*

Density of buildings	Consequence rating
Rural agriculture: 8 ha min. lot size	Low
Rural residential: 2 ha min. lot size	Moderate
Community: lot sizes < 2 ha	High

TABLE 3 *Risk rating*

Hazard (from Table 1)	Consequence (from Table 2)		
	High	Medium	Low
High	VH	H	M
Medium	H	M	L
Low	M	L	L

hazard on the fan. If the increases in peak flows from the sub-basin(s) will increase the hazard on the fan, then the ECA in the sub-basin(s) should be reduced to 20% or less, depending on the advice of the hydrologist and stream channel specialist.

If the risk rating for the watershed at the apex of the fan is Moderate or High, development should be deferred or modified or an avulsion risk assessment should be undertaken.

Fan Avulsion Risk Assessment

The fan avulsion risk assessment procedure is built upon work by Chatwin (1999). A hazard rating is derived using a stream power index and a sensitivity rating for the fan. The stream power index is obtained from Table 4. The stream power index varies according to the channel gradient and the cross-section. For example, the stream power index for a 2 m deep and 2 m wide channel on a 40% grade is Very High. A 1 m deep and 4 m wide channel on a slope less than 8% has a Moderate index.

The sensitivity of the fan to avulsion hazard is determined by a fluvial specialist using the following criteria (Chatwin 1999):

- degree of incision of channel(s)
- number of active channels
- amount of woody debris
- amount of stored sediment

Table 5 is used to establish an avulsion hazard rating, which is combined with the consequence rating to establish a risk rating for avulsion hazard on the fan (Table 3). Using this approach, a fan with more than two channels, a channel incision less than 1 m, large amounts of large woody debris, and large amounts of stored sediment in the channel will have a High sensitivity to destabilization (Chatwin 1999).

If the risk of avulsion is Low, no further analysis is required. If the risk is determined to be Moderate, High, or Very High, the development proposal is scaled back further or, alternately, a more detailed risk assessment can be undertaken, focusing on the channel capacity calculations.

TABLE 4 *Rating of stream channel power*

Channel gradient (%)	Channel cross-sectional area (m^2)				
	< 0.5	0.5–1.0	1.0–2.0	2.0–4.0	4.0–8.0
> 40	L	M	M	H	VH
20–40	VL	L	M	H	H
8–20	VL	L	L	M	H
< 8	VL	VL	L	L	M

TABLE 5 *Determining avulsion hazard*

Stream power index	Sensitivity of the fan Low	Moderate	High
Very low	VL	L	L
Low	VL	L	M
Moderate	L	M	H
High	L	H	VH

Channel Capacity Risk Assessment

A numeric model (HEC-RAS) is used to estimate water levels in the channel(s) associated with the increased discharges anticipated due to the development proposal. Inputs to the model include channel cross-sections, channel slope, channel roughness, and stream discharge (U.S. Army Corps of Engineers 1998). The HEC-RAS model, like all models, must be used with caution. The model operates on the assumption of a fixed bed geometry. During major floods, steep mountain streams usually experience large-scale bedload movement, channel shifting, and log jams. The one-dimensional fixed bed model does not take these conditions into account. However, because the objective is to assess future relative changes, the fixed bed model is considered appropriate for use in this application.

A flood discharge with a recurrence interval of 1 in 200 years (Q_{200}) is used as a basis for floodplain development control in the province and is considered an appropriate flood magnitude for this assessment procedure. Once an estimate is obtained for the Q_{200} (usually the annual maximum daily discharge), it is increased by the percentage increase in ECA associated with the development proposal. For example, if the estimated Q_{200} for the predevelopment period is 20 m^3/s and the proposed development plan is expected to increase the ECA to 25%, then the discharge used in the model would be 25 m^3/s. It is recognized that there is a risk of other processes, such as a rapid breach of a dam, channel blockage, or ice jamming, causing flood discharges and water levels higher than a predicted Q_{200} (Jakob and Jordan 2001). However, these occurrences are infrequent and the objective is to examine relative risk.

Tables 6 and 2 are used to determine the hazard and risk ratings. If the risk is Low no further analysis is required. If the risk is raised to the Moderate or High category, then the development proposal should be deferred or downsized.

RISK ASSESSMENT PROCEDURE FOR AREAS ABOVE DEBRIS FLOW FANS

This section describes a procedure for completing a watershed-scale risk assessment when field indicators (Figure 4), existing reports, and/or

TABLE 6 *Channel capacity hazard rating*

Channel clearance (at Q_{200} discharge)	Hazard rating
≥ 2 m to top of bank	Low
1–2 m to top of bank	Moderate
< 1 m to top of bank	High

professional opinion indicate that the dominant hazard on the fan is debris flow. The procedure generally follows the approach used by Boyer et al. (1999) in the *Perry Ridge Risk Assessment* report (see previous section).

In areas with obvious high risks, consideration should be given to having the assessment completed by an expert panel. Debris flow hazards are difficult to quantify. Consequently, most assessment reports depend heavily on professional judgement. A panel of experts can provide a consensual risk assessment, which is more reliable than one prepared by a single professional. Ideally, the team would consist of a geomorphologist, a forest hydrologist, and a forester. In less sensitive / less contentious watersheds with lower consequences, a qualified professional can do the assessment. A peer review of the report by an independent expert will increase the confidence in the risk assessment.

The assessors should become familiar with the terrain where development is proposed and where previous activity has occurred in the watershed by taking a helicopter overview flight and/or spending a few days in the field. The assessor should also converse and/or go into the field with authors of supporting documents, such as terrain stability field assessment (TSFA) reports and channel assessments.

Event Types

The first step is to identify the types of geological hazards present in the watershed that could have an effect on the fan. These hazards usually include debris flows (including debris torrents and debris floods) and snow avalanches. On rare occasions, fans are flooded by the mass movement of snow and slush during a rapid warming event in winter floods fans.

Assessing Existing Hazards

All available information, helicopter overview flights, and a few days in the field (depending on the size and sensitivity of the watershed) are used to identify landslide- and snow avalanche-sensitive terrain in the watershed. A stream channel survey procedure developed for the Perry Ridge study by Chatwin is used to assist in the assessment of gully and headwater stream channels (Chatwin 1999). Existing roads, trails, cutblocks, and/or mining disturbances (tailing ponds, waste piles, old structures such as dams, etc.) on or above steep unstable terrain must be included in the assessment.

Fan Hazard Ratings for Existing Condition

Once unstable and/or potentially unstable areas are identified, linkages or connectiveness between these sites and the fan are assessed. This assessment is undertaken using professional judgement and all existing information, including stream channel inventory and rating information (Chatwin 1999). Additional field reviews may be warranted for high-risk sites. Each event type is assigned a hazard rating using the following three-class rating system: Low, Moderate, and High.

Rating Hazards with Consideration of Development Effects

Once the existing hazards are rated, the influence of the proposed development on these ratings is assessed.

Roads, trails, cutblocks, or other disturbances proposed on or above identified and suspected unstable terrain must be assessed. These include hazards associated with flat-over-steep scenarios (Jordan 2001). Each site should be viewed in the field, with special attention paid to potential micro-drainage problems (Green and Halleran 2002). When timber harvesting is proposed on or above steep unstable terrain, micro-drainages should be mapped and verified in the field to assess the risk of landslide initiation by drainage concentration or diversion. ECAS should be calculated to assess the risk of localized peak flow increases causing landslide initiation.

If there are proposed clearcut areas in potential snow avalanche start zones and the assessment team or qualified professional does not have experience with the detection and prediction of snow avalanches, a specialist should be retained to assess snow avalanche hazards.

Stream channel surveys (Chatwin 1999) are used to assess the linkages associated with proposed development.

Hazard assessment should consider all possible spatial and temporal effects of the proposed development. Disturbance effects can be long lasting and require a continued site commitment until hydrological recovery and/or road deactivation works take hold. On or near unstable terrain, there is a certain degree of risk of a landslide or erosion event whenever a road segment is left through a winter with open ditches and culverts. Road cutbank failures and culvert blockage can go undetected and can occur during spring breakup when workers and equipment cannot access the site(s).

RISK ANALYSIS

Hazard ratings are combined with consequence ratings (Table 2) to assign a final risk rating for the fan using Table 3.

Areas where proposed development poses a high risk should be rejected from the plan. Areas generating a moderate risk should also be deferred unless a combination of project modifications and/or special best management practices can mitigate the hazard effects from the development proposal (i.e., move the risk rating for the project into the Low category). Proposed best management practices recommended and the company proposing them should have a proven track record.

CONCLUSION

A procedure for assessing increased risk on alluvial and colluvial fans associated with resource development proposals is presented.

REFERENCES

Boyer, D. 1999. Debris flow hazards on alluvial fans: Kootenay Region, southeast B.C. *In* Proc. Confronting Uncertainty: Managing Change in Water Resources and the Environment, Richmond, B.C. Can. Water Resources Assoc., B.C. Br., pp. 325–7.

Boyer, D., P. Jordan, and D.F. VanDine. 1999. Perry Ridge risk assessment. Report and maps prepared for the Perry Ridge Local Resource Use Plan Table. B.C. Min. For., Arrow Forest District, Castlegar, B.C.

British Columbia Ministry of Forests. 1999. Watershed assessment procedure guidebook. 2nd ed., Version 2.1. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

Chatwin, S. 1999. Perry Ridge stream channel survey. Prepared for B.C. Min. For., Arrow Forest District, Castlegar, B.C.

Green, K. and W. Halleran. 2002. Drainage plans: A comprehensive planning tool in high-risk terrain. *In* Terrain Stability and Forest Management in the Interior of British Columbia: Workshop Proc. P. Jordan and J. Orban (editors). Nelson, B.C., May 23–25, 2001. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

Jackson, L.E. Jr., R.A. Kostaschuk, and G.M. McDonald. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. Geol. Soc. Am. VII:115–24.

Jakob, M. and P. Jordan. 2001. Design flood estimates in mountain streams – the need for a geomorphic approach. Com. J. Civ. Eng. 28:425–39.

Jordan, P. 2001. Regional incidence of landslides. *In* Proc. Watershed Assessment in the Southern Interior of British Columbia. D.A.A. Toews and S. Chatwin (editors). B.C. Min. For., Res. Br., Victoria, B.C. Work. Pap. 57/2001, pp. 237–47.

Klohn Crippen Consultants Ltd. 1998. Terrain stability inventory alluvial and debris torrent fans, Kootenay Region. Report prepared for B.C. Min. Environ., Lands, and Parks, Nelson, B.C. Rep. 1020.

Melton, M.A. 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. J. Geol. 73:1–38.

U.S. Army Corps of Engineers. 1998. HEC-RAS river analysis system user's manual version 2.2. U.S. Army Corps of Engineers Manual. Davis, Calif.

VanDine, D.F., D. Boyer, and P. Jordan. 1999. Perry Ridge, an example of a risk assessment for forestry planning. *In* Proc. Confronting Uncertainty: Managing Change in Water Resources and the Environment, Richmond, B.C. Can Water Resources Assoc., B.C. Br., pp. 255–62.

Whitaker, A., Y. Alila, and D.A.A. Toews. 2001. Modeling of peak flow change using the DHSVM model. *In* Proc. Watershed Assessment in the Southern Interior of British Columbia. D.A.A. Toews and S. Chatwin (editors). Penticton, B.C. B.C. Min. For., Res. Br., Victoria, B.C. Work. Pap. 57/2001, pp. 94–111.

Recommended Procedure for Conducting Studies in Support of Land Development Proposals on Alluvial and Debris Torrent Fans

DWAIN BOYER

ABSTRACT

Alluvial and debris torrent fans are common landforms in the Kootenay Region of British Columbia. Rapidly melting snow, heavy rains, channel blockages, and landslides can result in avulsions, debris torrents, or debris floods on these fans. Private and public lands, infrastructure, and people occupying the fans are at risk during these extreme events. The provincial government has policies to help reduce the risk of injury to people and to avoid property damage at the land subdivision level. The objectives of this presentation are to explain these policy and procedures, to recommend hazard acceptability thresholds for use when preparing engineering reports in support of subdivision applications, and to provide a guide for the preparation of risk assessment reports.

PURPOSE

The purposes of this presentation are:

1. to explain existing policy and procedure for subdivision approval on high-hazard alluvial and colluvial fans in southeastern British Columbia;
2. to recommend hazard acceptability thresholds for use in the adjudication of subdivision applications on high-hazard alluvial and colluvial fans; and
3. to provide a guide for risk assessment reports prepared in support of subdivision applications on high-hazard alluvial and colluvial fans.

EXISTING SUBDIVISION APPROVAL PROCESS FOR ALLUVIAL AND DEBRIS FLOW FAN AREAS IN SOUTHEASTERN BRITISH COLUMBIA

Land use planning is the responsibility of local governments (municipalities and regional districts). The provincial Ministry of Water, Land and Air Protection (WLAP) assists local governments by providing maps showing areas affected by water-related hazards. Local governments use these maps for official community plans, bylaws, and development permit area designations to encourage the use of these areas for open spaces such as parks. The goal is to keep high-consequence uses, such as residential or commercial, clear of these areas.

Subdivision and building permitting processes are used to regulate land use on alluvial and debris flow fans. In British Columbia, subdivisions are approved by subdivision approval officers (Table 1). In rural, unincorporated

TABLE 1 *Land development proposals: jurisdiction, enabling legislation, and policies related to alluvial and debris flow fans*

Type of development proposal	Jurisdiction		Enabling legislation	Policy related to alluvial and debris flow fans
	Inside municipality	Outside municipality		
Subdivision	Municipal subdivision approval officer	Provincial approval officer: MOT[a]	*Land Title Act* Section 82 (1)[b]	WLAP:[c] • Development discouraged. • Where there is no alternative land available and where an area of the fan can be shown to be stable because of hydraulic, physical, and/or geological conditions, consent to develop may be granted.[d] • Conditions on the consent to develop may include floodproofing / debris flow protection requirements, density regulations, and provision of protective work. MOT: • In the case of debris torrents, debris flows, or debris floods, the proponent must prove that the proposed development is safe or can be made safe when considering an event with a 10% chance of occurrence over a 50-year period (reference MOT Hazards).
Building permit	Municipal building inspector	Regional district building inspector[e]	*Local Government Act* Section 699; Section 910[f]	• Some municipalities and regional districts have developed brochures to guide developers through the approval process for building permits (examples provided in reference list). One regional district, the Fraser-Cheam Regional District, has also developed a risk matrix.

[a] If the property is situated on an alluvial or debris flow fan, the subdivision approval officer (SAO) will refer the proposal to WLAP for comment. The SAO may also refer the proposal to the MOT Geotechnical Engineering Section for comments when a debris flow or other landslide hazards have been identified.

[b] http://www.qp.gov.bc.ca/statreg/stat/L/96250_07.htm - section 82

[c] Development on alluvial fans should be retained in non-intensive uses such as parks, open-space recreation, and agricultural uses. All development is discouraged when there is a flood hazard associated with the more destructive debris flow hazard.

[d] If protective works are required, they will have to be designed and constructed under the supervision of a suitably qualified professional engineer or geoscientist prior to subdivision approval. Furthermore, local government will be required to accept ownership of the works and agree to maintain the works. To facilitate this, site plans, easements, and operations and maintenance manuals are required. If the works, when constructed, will protect more than one property, then the structure may require the additional approval of the Inspector of Dikes. See http://www.qp.gov.bc.ca/statreg/stat/D/96095_01.htm for information on the *Dike Maintenance Act*.

[e] Building inspection bylaws are not mandatory for regional districts. In some regional district areas, there are no controls on land development on hazardous lands.

[f] http://www.civicinfo.bc.ca/lga/part_21/part_21.htm#sec699
http://www.civicinfo.bc.ca/lga/part_26/part_26.htm#sec910

areas, subdivisions are approved by the B.C. Ministry of Transportation (MOT) approval officer. In municipalities, subdivisions are approved by municipal approval officers. The B.C. Ministry of Water, Land and Air Protectionprovides conditions for subdivision approval when the land proposed for subdivision is subjected to a flooding and/or alluvial fan and debris flow hazard (Table 1).

The B.C. Ministry of Water, Land and Air Protection's policy requires active alluvial fans and areas subject to debris flow hazard to be kept clear of development, except where it can be shown that there is no other land available and that the potential property damage and danger to human life are low and adequate protection can be provided. In southeastern British Columbia (Kootenay Region), WLAP has compiled an inventory of known alluvial and debris flow fans along populated travel corridors (Klohn Crippen Consultants Ltd. 1998; Boyer 1999). This information will soon be available on WLAP's regional Web site.

The B.C. Ministry of Transportation also has a subdivision policy with respect to debris flow hazard (MOT 1996). This policy will be discussed in the next section.

ACCEPTABLE RISK LEVELS

Existing Government Policy on Acceptable Risk

B.C. Ministry of Transportation policy requires the engineer reporting on a subdivision application involving land subject to a debris flow hazard to think in terms of a 10% chance of occurrence of the hazard over a 50-year period. This translates into an annual probability of 1 in 475. MOT policy does not have any statements concerning the magnitude of events and does not provide guidelines for reporting requirements.

The B.C. Ministry of Water, Land and Air Protection's policy and procedures state that residential and commercial development must be discouraged on active alluvial fans and areas subject to a debris flow hazard. The policy does not provide guidance on what constitutes an "active" alluvial or debris flow fan. WLAP has detailed policy and procedures, including an acceptable risk threshold (1 in 200 years) and definitions for stream and lake flooding. However, this policy does not apply to alluvial and colluvial fans.

Before approving a building permit in identified high-hazard areas, most local governments will require an engineering report (Table 1). Note that not all local governments have building bylaws or building inspectors. The engineer must demonstrate that the land is "safe for the use intended." Most local governments do not have policy on acceptable risk or a definition for "safe for the use intended." Instead, the onus is put on the engineer to decide what acceptable risk is. Many engineers are uncomfortable with this role. There is a general expectation that government should set acceptable risk levels.

One regional district, the Fraser-Cheam Regional District (FCRD), has policies on hazard acceptability thresholds for land development (Cave 1991). FCRD approves development proposals without siting conditions and/or protection works when the estimated annual probability of occurrence of the event affecting the property is reported to be in the range identified in Table 2.

The Fraser-Cheam Regional District policy states that subdivisions can be approved with siting conditions and protective works or both and a "save harmless" covenant at the threshold values listed in Table 3.

TABLE 2 *Hazards and acceptable thresholds for subdivision approval without siting conditions or protective works*

Hazard	Annual Probability
Avulsion	less than 1:500
Debris flood	1:500 to 1:10 000[a]
Debris flow / debris torrent	less than 1:10 000

[a] Development can be approved with siting conditions or protective works but with a "save harmless" covenant registered on title.

RECOMMENDED ACCEPTABLE RISK LEVELS FOR SUBDIVISION APPROVAL

The acceptable risk levels quoted in Tables 2 and 3 should be adopted by the province for the adjudication of applications on fans. Where structures and/or channel maintenance work is required to provide the required level of protection, a local authority must be established to inspect and maintain the works. Subdivisions should not be approved without a commitment from local government to take on this responsibility. This topic is discussed further in the "Mitigation Works" section.

The risk levels quoted in Tables 2 and 3 were based on the few guidelines available at the time (Cave 1991). The guidelines or yardsticks used include the following:

- The 1-in-200-year threshold used by WLAP for flooding.
- The 1-in-475-year threshold used by MOT for landslide hazards.
- A 1973 B.C. Supreme Court decision (Rubble Creek), which found a site exposed to a 1-in-10 000-year probability of landslide occurrence to be unsuitable for development. In this case, the development would have formed the nucleus of a new community while the suspected hazard type was a massive and destructive landslide (Cave 1991).

No new provincial guidelines have been developed for dealing with land development proposals that account for acceptable risk levels since 1991. However, many practitioners have quoted these values as "industry standards" and there is a need for the province to adopt a policy statement for making decisions on subdivision applications.

Data to make quantitative probability estimates for avulsion, debris flood, and debris flow/torrent events are difficult and costly to acquire. Sometimes, no data are available. Consequently, most quantitative probability estimates made in British Columbia are based on subjective means of evaluation. Although a hazard may occur within a subjectively estimated probability limit, it may occur at any time. When an anticipated hazard occurs, new quantitative probability estimates must be established. Also, initial quantitative probability

TABLE 3 *Hazards and acceptable thresholds for subdivision approval with siting conditions and/or protective works and covenant*

Hazard	Annual Probability
Avulsion	1:200 to 1:500
Debris flood	1:200 to 1:500
Debris flow / debris torrent	1:500 to 1:10 000

estimates may be affected by unanticipated or unrecorded events. The useful "lives" of quantitative or qualitative probability estimates are rarely considered (Thurber 2000). Consequently, professionals should use the threshold values in Tables 2 and 3 in the same context as the MOT policy (i.e., the approval authority and the professional undertaking the risk assessment should "think in terms of the applicable range of threshold values"). Professionals are obligated to determine current states of hazard in follow-up work (Thurber 2000).

DISCUSSION ON REPORT CONTENT

Professionals making land use recommendations for alluvial and/or colluvial fan areas must first determine what the risk is on the property and then compare this risk against acceptable risk criteria. They must then summarize their findings in a report with sufficient detail and content to facilitate a professional review of the study.

When evaluating subdivision proposals and building permit applications in high-hazard areas, government officials rely on these reports. Government officials have a duty of care to review engineering/geoscientist reports to ensure that the engineers/geoscientists appear qualified and have used appropriate data and methodology in assessing the level of risk a development will face. When things go wrong, courts tend to pull in the approval authorities (as deep pockets), in addition to the proponents and their engineers/geoscientists. Investigating professionals may save a great deal of time and client's money, and avoid misunderstandings, if they contact the reviewing agency at the initiation of the investigation (California Department of Conservation 2000).

Geological hazard mapping is a specialized form of professional engineering and geoscience work. In a report prepared for WLAP, Thurber Engineering Ltd. found that some U.S. jurisdictions require independent third-party reviews of engineering and geologic reports that deal with geologic hazards (Thurber 2000).

Most decisions regarding acceptable risk depend heavily on field observations and expert opinion. Intellectual basis for quantitative probability estimates without documented age controls are subject to debate. There are reasonable grounds and circumstances for specialists to make these estimates in British Columbia. However, estimates of hazard return periods greater than 200–300 years require considerable qualifications (Thurber 2000).

A peer review and/or consensus decision-making can increase the confidence and acceptability of risk assessment reports. Peer review involves the employment of a recognized specialist to complete a review of the report prior to its submission to government. The consensus decision process operates on the premise that two or more heads are better than one (Chantler et al. 2001). It involves the forming of a multidisciplinary team of professionals with experience in surficial and fluvial geomorphology and forest hydrology.

In many situations, a phased approached to reporting the hazard is appropriate. A preliminary overview assessment can provide the landowner with an indication of whether or not the land is safe and how much it will cost to provide a detailed report.

SUGGESTED OUTLINE FOR A FAN STUDY

This section provides a suggested outline for a fan study. The outline is not intended to restrict the content of any professional engineering/geoscientist report. From a professional practice perspective, quantitative or qualitative probability estimates should not substitute for intensive geologic and engineering investigations, which apply engineering analytic methods, if required (Thurber 2000). Some hazards will be easier to identify than others and site conditions will vary. Consequently, some projects may not require all the data and analyses listed in this outline. It should, however, serve as a checklist.

Maps

1. **Location map**

- approximate scale 1:250 000

2. **Watershed and fan map** (See Figure 1)

- approximate scale 1:20 000 to 1:50 000
- watershed boundaries
- contours
- planimetric information
- fan boundaries
- watershed information themes including terrain stability map polygons, soils information, roads, cutblocks, landslides

3. **Fan Map** (See Figure 2)

- 1:5 000 to 1:10 000 scale
- fan boundaries
- fan hazard zones
- proposed development area property boundaries
- planimetric details: roads, utilities, houses, etc.
- sufficient contour information to describe terrain upslope from the proposed development on the fan
- soils mapping
- terrain stability map polygons
- stream channels
- hydraulic structures
- log jam sites
- potential avulsion points (see Figure 3)
- flood/debris control structures: existing and proposed
- geomorphic features: levees, lobal features, abandoned channels, etc.
- carbon dating sampling sites
- test pits
- location of cross-section lines
- debris flow runout paths
- landforms and other features that may influence overland flow paths, debris flow, or flooding

Profiles
(See Figure 4)

- main channel thalweg from the height of land in the watershed to toe of fan

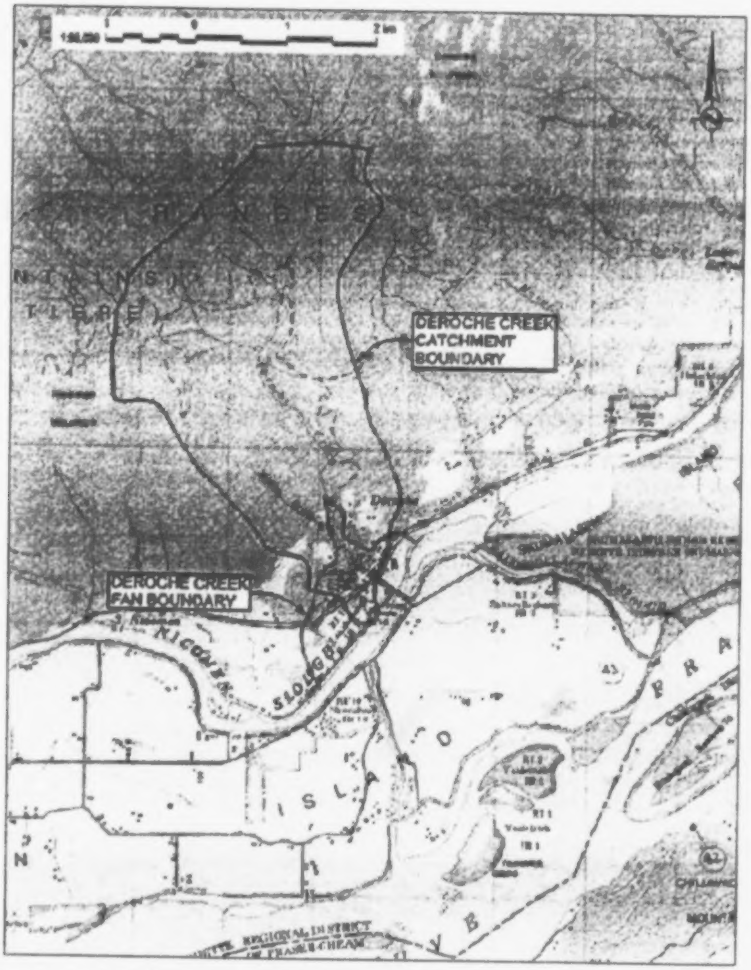


FIGURE 1 *Sample watershed and fan map (Chantler et al. 2001).*

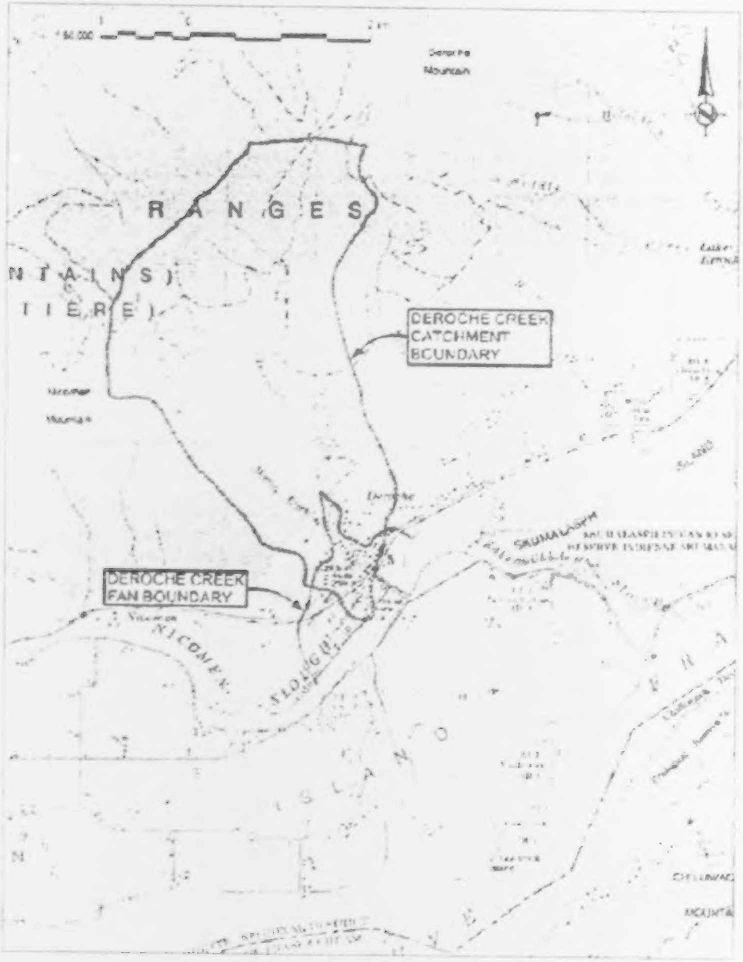
- stream thalweg from the fan apex to fan toe
- likely avulsion and debris flow runout paths
- fan apex through development proposal

Cross-Sections
(See Figure 5)

- channel cross-section detail showing estimated Q_{100} water levels and/or dam burst water levels
- fan surface transects

Text

- description of watershed area: bedrock types, surficial geology, level of disturbance (road densities and equivalent clearcut area), terrain stability information, watershed area, relief, basin length, basin shape, length of stream channels, designation of unstable or potential unstable slopes, road deactivation information, stream restoration activities
- description of local climate and hydrology: annual precipitation amounts, rainfall intensity/duration curves, typical hydrograph
- predominant hazard (fluvial, debris torrent, debris flood, outbreak floods


1:50,000
2 km
Deroche Mountain
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MOUNTA

FIGURE 1 *Sample watershed and fan map (Chantler et al. 2001)*

- stream thalweg from the fan apex to fan toe
- likely avulsion and debris flow runout paths
- fan apex through development proposal

Cross-Sections
(See Figure 5)

- channel cross-section detail showing estimated Q_{200} water levels and/or dam burst water levels
- fan surface transects

Text

- description of watershed area: bedrock types, surficial geology, level of disturbance (road densities and equivalent clearcut area), terrain stability information, watershed area, relief, basin length, basin shape, length of stream channels, designation of unstable or potential unstable slopes, road deactivation information, stream restoration activities
- description of local climate and hydrology: annual precipitation amounts, rainfall intensity/duration curves, typical hydrograph
- predominant hazard (fluvial, debris torrent, debris flood, outbreak floods)

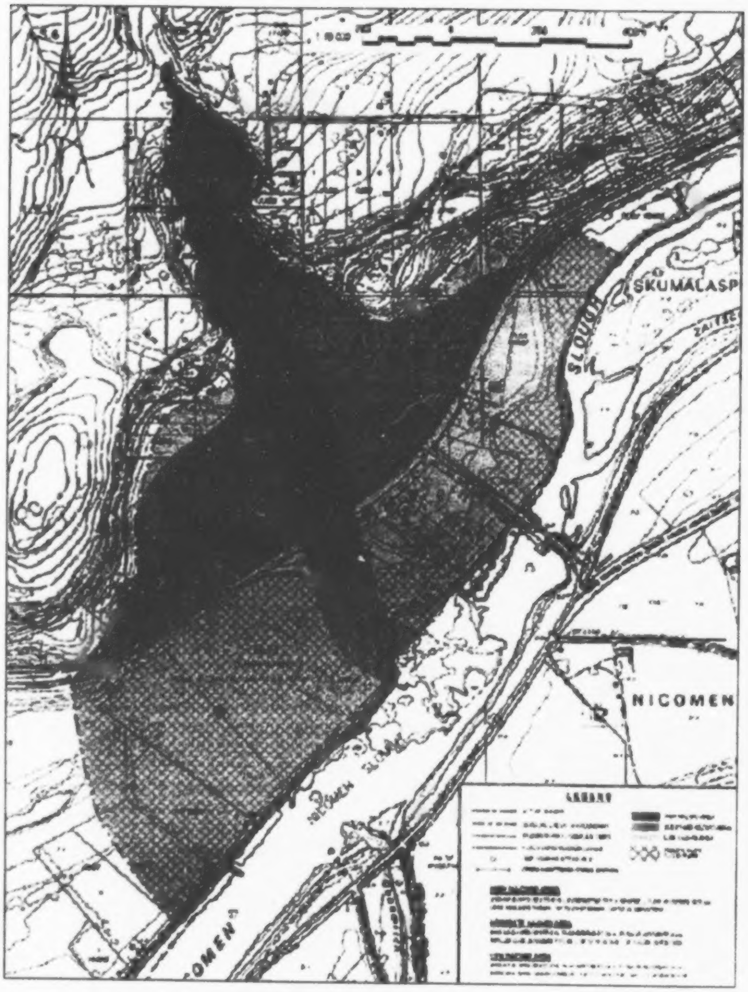
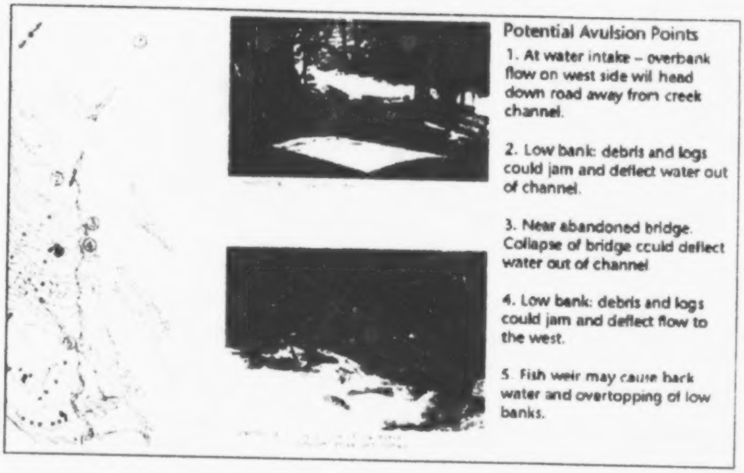


FIGURE 2 *Sample fan map (Chantler et al. 2001).*

[see Figure 6]) from landslide dams or combination thereof, and method of determination

- summary of existing reports containing watershed information: Interior Watershed Assessment Reports, terrain stability reports, sediment source surveys, channel assessment reports, watershed restoration reports
- description of fan area: surficial geology, geomorphic features, description of deposits (mode of deposition, stratification, grading, sediment characteristics). Note: Harvesting of the fan itself can lead to further instabilities, as noted by Wilford et al. (2002)
- vegetation indicators (scarred trees, dendrochronology, traces of events outlined by varying vegetation types), hydraulic structures, avulsion points (assess existing channel capacity using HEC-RAS), area, slope
- summary of existing reports containing information on the fan area: engineering reports prepared for/by MOT (for subdivision and/or hydraulic structures), WLAP, local government, utilities, railway


Potential Avulsion Points

1. At water intake – overbank flow on west side wil head down road away from creek channel.

2. Low bank: debris and logs could jam and deflect water out of channel.

3. Near abandoned bridge. Collapse of bridge ccuid deflect water out of channel

4. Low bank: debris and logs could jam and deflect flow to the west.

5. Fish weir may cause back water and overtopping of low banks.

FIGURE 3 *Sample potential avulsion points–Redfish Creek (Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd. 1990).*

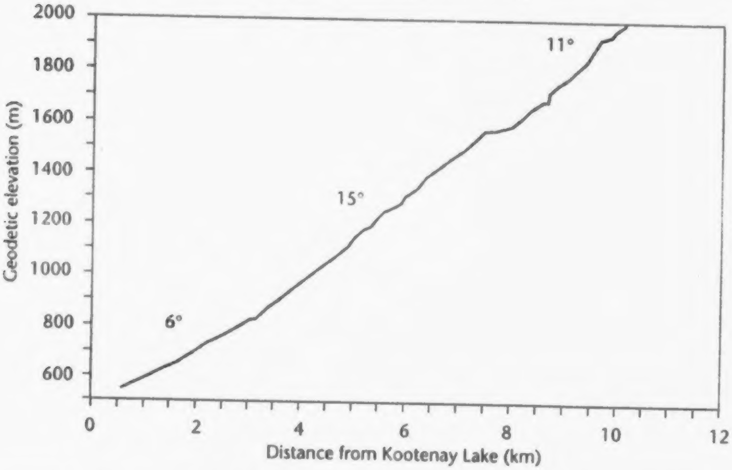


FIGURE 4 *Sample valley profile–Narrows Creek (Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd. 1990).*

- assessment of watershed process impacts on fan hazard
- historical flooding / debris flow information: region- and watershed-specific
- Melton's ruggedness index
- channel gradient and condition upslope of fan
- hydrology: determine worst-case flood scenario (Q_{200} or dam burst discharge event)
- debris flow volume estimate and velocity estimates and method of determination.
- debris flow runout distance estimates and method of determination runout modelling: Hungr DAN model
- statement of regional government jurisdiction and floodplain bylaw requirements

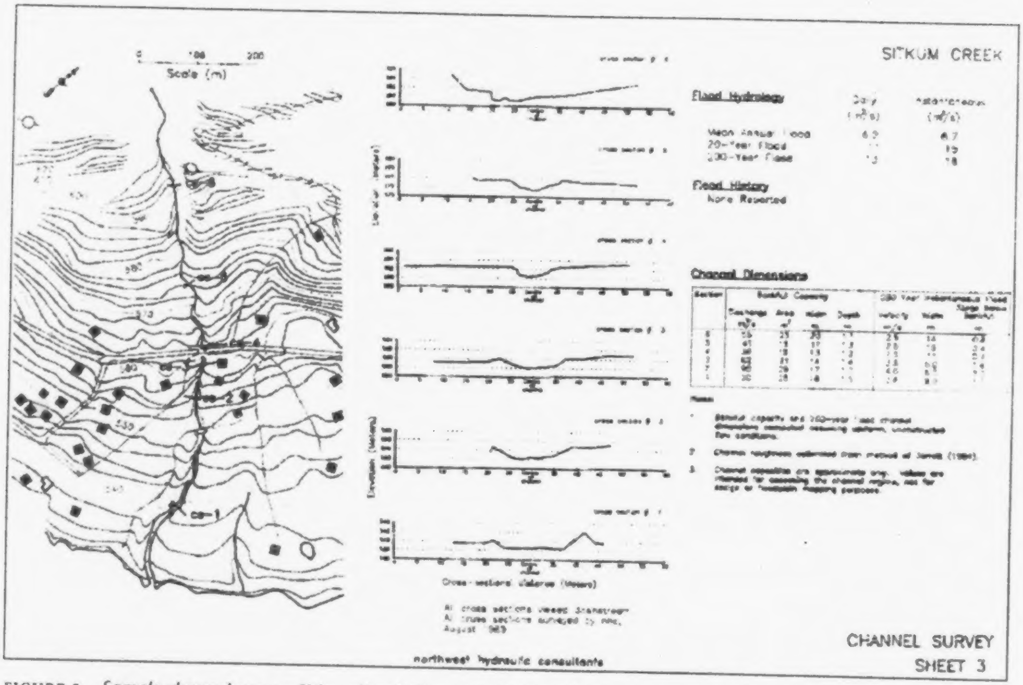

Scale (m)
SITKUM CREEK
Flood Hydrology
Mean Annual Flood
20-Year Flood
200-Year Flood
Flood History
None Reported
Channel Dimensions
Cross-sectional distance (Meters)
CHANNEL SURVEY
SHEET 3
northwest hydraulic consultants

FIGURE 5 *Sample channel survey–Sitkum Creek (Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd. 1990).*

- title search for restrictive covenants on the property proposed for development
- review of air photography from date of first flights to present condition (see Figure 7)
- agencies contacted
- photo documentation
- if mitigation works are recommended, provide a separate package containing written commitment from local government to assume ownership of works, design calculations, plans, cross-sections and specifications, and access provisions. Development is often not approved, because local government and/or the local citizens are not willing to assume ownership of flood and/or debris flow control works. The developer and/or their consultant should not proceed with design work until WLAP approves the project in concept and the local government commitment to ownership and maintenance of the works is secured.
- discussion of potential effects of any proposed flood or debris flow control works on other properties, roadways, utilities, and hydraulic structures
- quantitative probability estimate and rationale

MITIGATION WORKS

Engineering/geoscientist reports often recommend approval of subdivision proposals with conditions, such as the construction of debris flow or river

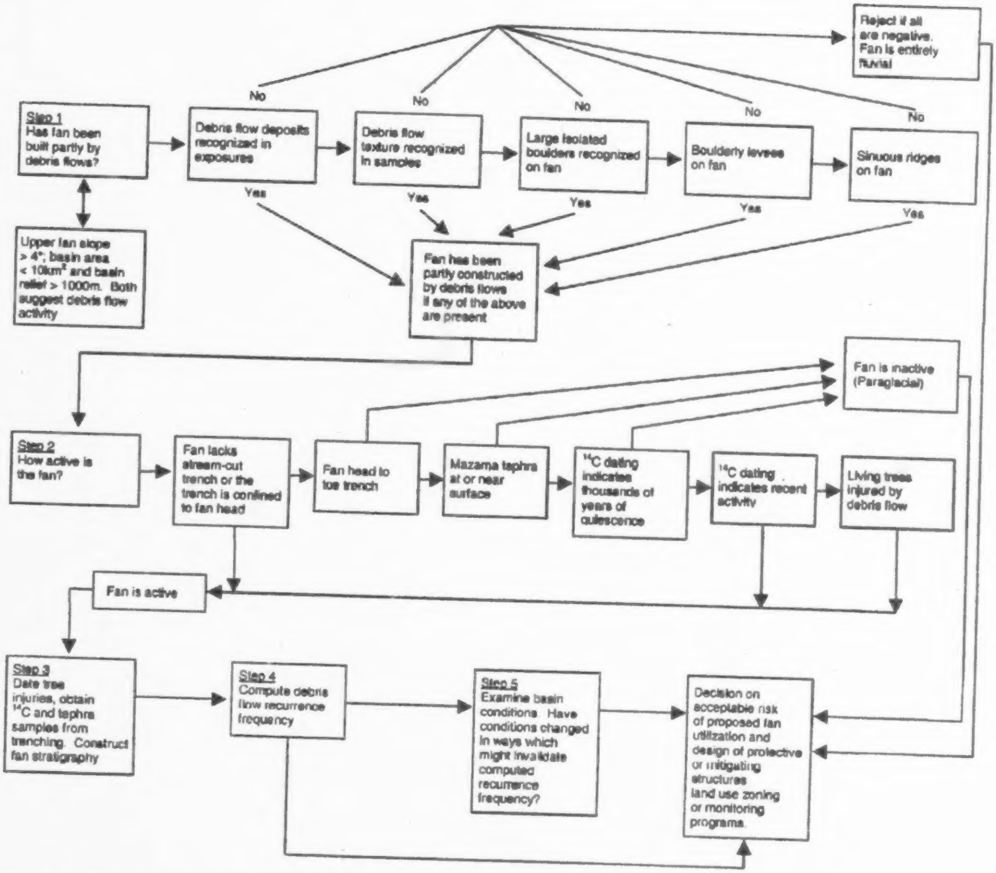

Reject if all are negative. Fan is entirely fluvial
No
No
No
No
No
Step 1
Has fan been built partly by debris flows?
Debris flow deposits recognized in exposures
Debris flow texture recognized in samples
Large isolated boulders recognized on fan
Boulderly levees on fan
Sinuous ridges on fan
Yes
Yes
Yes
Yes
Yes
Upper fan slope > 4°; basin area < 10km² and basin relief > 1000m. Both suggest debris flow activity
Fan has been partly constructed by debris flows if any of the above are present
Fan is inactive (Paraglacial)
Step 2
How active is the fan?
Fan lacks stream-cut trench or the trench is confined to fan head
Fan head to toe trench
Mazama tephra at or near surface
¹⁴C dating indicates thousands of years of quiescence
¹⁴C dating indicates recent activity
Living trees injured by debris flow
Fan is active
Step 3
Date tree injuries, obtain ¹⁴C and tephra samples from trenching. Construct fan stratigraphy
Step 4
Compute debris flow recurrence frequency
Step 5
Examine basin conditions. Have conditions changed in ways which might invalidate computed recurrence frequency?
Decision on acceptable risk of proposed fan utilization and design of protective or mitigating structures land use zoning or monitoring programs.

FIGURE 6 *Flow diagram summarizing debris flow hazard evaluation method (Jackson 1987).*

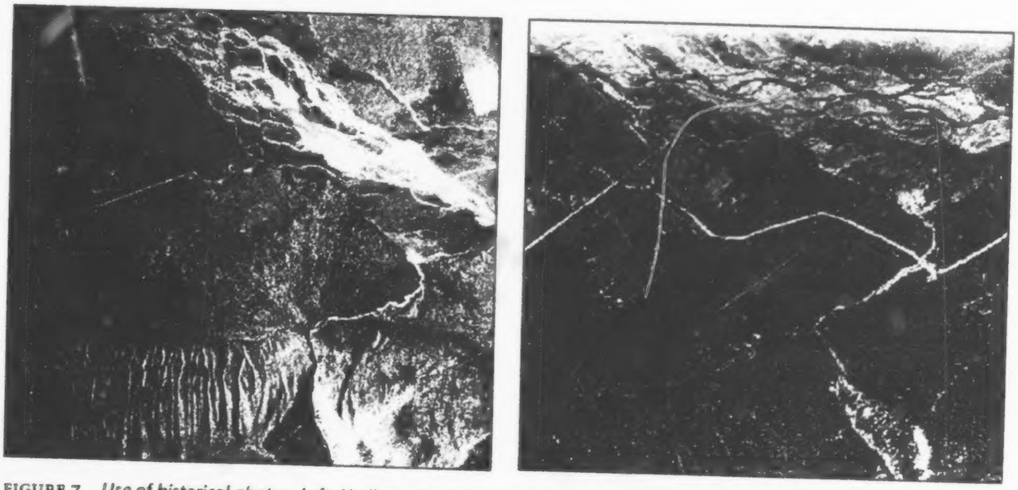


FIGURE 7 *Use of historical photos. Left: Hedberg Creek Fan 1945. Right: Hedberg Creek Fan 1986.*

training works and/or channel monitoring and maintenance. In many instances, these proposals cannot be approved because local governments and/or local residents do not agree to take ownership of the works and maintain them.

The developer and/or consultant should not waste time and money on detailed design reports and/or construction projects without a prior commitment from local government to maintain the works. At a minimum, the local authority will require unobstructed legal access for carrying out inspections and repairs and for producing monitoring reports, as-built plans, and, in some cases, operation and maintenance manuals. The Province will require the construction and certification of the works by a professional engineer prior to giving subdivision approval.

The works may have to be registered in the provincial registry of dikes and receive a separate approval from the Inspector of Dikes. The province may require restrictive covenants on properties as an extra measure of safety. Restriction on title may include elevating any dwelling above the ground level on protected fill, and density controls.

SUMMARY/CONCLUSIONS

Property owners and/or developers with a desire to develop property on active or potentially active alluvial or colluvial fans may be required to obtain government approval. For development activity requiring subdivision approval, the owner/developers will usually be required to obtain prior approval from local and provincial governments. For development activity requiring a building permit, the owner/developer may be required to obtain prior approval from local government. This document provides a summary of the approval requirements pertaining to alluvial and colluvial fans in British Columbia.

REFERENCES

BC Hydro. 1993. Geotechnical guidelines for determining slope stability and groundwater impacts on reservoir shorelines for land use purposes. Rep. H2293.

———. 1994. Recommended procedures for conducting studies in support of a safeline variance request. Rep. H2879.

Boyer, D. 1999. Debris flow hazards on alluvial fans: Kootenay Region, southeast B.C. *In* Proc. Confronting Uncertainty: Managing Change in Water Resources and the Environment, Richmond, B.C. Can. Water Resources Assoc., B.C. Br., pp. 325–7.

California Department of Conservation, Division of Mines and Geology. 2000. General guidelines for reviewing geologic reports. Note 41. http://www.consrv.ca.gov/dmg/pubs/notes/41/index.htm.

Cave, P.W. 1991. Hazard acceptability thresholds for development approvals by local government. B.C. Geologic Hazards Workshop, Feb. 20–21, 1991, Victoria, B.C. B.C. Min. Energy, Mines, and Petroleum Resources.

———. 1992. Legal instruments and techniques for implementing hazard land planning policies in British Columbia. Report prepared for B.C. Min. Municipal Affairs, Victoria, B.C.

Chantler, A., M. Jakob, and G. Farstad. 2001. Flood hazards at Deroche Creek—an interdisciplinary approach. *In* Proc. Changing Water Environments: Research and Practice, Whistler, B.C. Can. Water Resources Assoc., B.C. Br. (published as CD). Flood Studies, pp. 10–6.

District of North Vancouver. 2000. District of North Vancouver Master Requirement SPE106 – Flood Hazard Report Section 219. Covenant document no. 176121, North Vancouver, B.C.

Jackson, L. 1987. Debris flow hazard in the Canadian Rocky Mountains. Geol. Surv. Can. Paper 86-11.

Klohn Crippen Consultants Ltd. 1998. Terrain stability inventory alluvial and debris torrent fans, Kootenay Region. Report prepared for B.C. Min. Environ., Lands, and Parks, Nelson, B.C. Rep. 1020.

Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd. 1990. Alluvial fan hazard assessment, Regional District of Central Kootenay Area "E" and "F". Report prepared for B.C. Min. Environ., Lands, and Parks, Nelson, B.C. Rep. 965.

Regional District of Central Kootenay. 1993. A guide to floodplains, alluvial fans and other geotechnical hazards. Regional District of Central Kootenay Brochure. Nelson, B.C.

———. 1996. Terms of reference for minimum requirements for engineers undertaking geotechnical reports on lands within special policy areas as defined in Schedule "E" of Floodplain Management Bylaw 1000, 1993. Regional District of Central Kootenay Brochure. Nelson, B.C.

Regional District of Fraser-Cheam. 1991. Assistance to developers and building permit applicants undertaking geotechnical studies. Regional District of Fraser-Cheam Brochure. Chilliwack, B.C.

Thurber Engineering Ltd. 2000. Review of policies and procedures for lease or sale of public lands subject to debris flow and related hazards. Report prepared for B.C. Min. Environ., Lands and Parks, Lower Mainland Region. Surrey, B.C.

Wilford, D., M. Sakals, and J. Innes. 2002. Forestry on fans: Identifying hydrogeomorphic hazards. *In* Proc. Terrain Stability and Forest Management in the Interior of British Columbia. P. Jordan and J. Orban (editors). Nelson, B.C., May 23–25, 2001. B.C. Min. For., For. Sci. Program, Victoria, B.C. Tech. Rep. 003.

Landslides in Cretaceous Interbedded Sandstone, Mudstone, and Shale in the Fort St. John Forest District, British Columbia

ZHONGYOU LU AND MARC ST. ARNAUD

ABSTRACT

The Fort St. John Forest District in northeastern British Columbia is widely underlain by Cretaceous interbedded sandstone, mudstone, and shale. Numerous landslides have occurred along streams cutting into these Cretaceous sedimentary rocks and in the weathering products or displaced materials derived from these rocks. Surfaces of rupture of the rockslides in Cretaceous rock often follow gently dipping bedding planes, especially bedding planes in shale. The dip angle of major rupture surfaces can be as gentle as 5°. The boundaries of these rockslides generally follow steeply dipping joints. River down-cutting plays a very important role in the initiation of these rockslides. These large, deep-seated rockslides would not occur without the exposure of weak bedding planes along streambanks. The rockslides observed in the field located on the banks along incised streams and the main part of the upland surface remain stable. These features are obvious clues to recognize the importance of river down-cutting in landslide initiation in the area. Groundwater has played an important role in the initiation of these rockslides by reducing shear strength along potential rupture surfaces. Unlike other types of rockslides (e.g., those developed in limestone, sandstone, and quartzite in the Rocky Mountains in both Alberta and British Columbia), the landslide deposits of rockslides and their weathering products in the study area may move again and again. Debris slides and debris flows are also seen on the displaced materials in incised stream valleys in the Fort St. John Forest District. As a result, different types of landslides—rockslides, debris slides, and debris flows—occur in groups and move repeatedly in the study area. Cretaceous interbedded sandstone, mudstone, and shale, and their weathering products, are the most landslide-prone materials in the Fort St. John Forest District. A clear understanding of the local geologic controls on landslide activity will enhance forest management in the district. We suggest that detailed terrain stability mapping and terrain stability field assessments should be concentrated on the slopes along deeply incised streams in the study area. Sometimes it is difficult to recognize large, deep-seated landslides within cutblocks, and some of these landslides may move rapidly. Therefore, detailed air photo interpretation and field investigation in the study area by experienced terrain specialists are strongly recommended.

The Alberta Plateau of the Interior Plains of British Columbia is a natural continuation into British Columbia of the Alberta Plateau, a physiographic unit that is also present in western Alberta. The plateau stands at between 900 and 1200 m in the Fort St. John Forest District.

The study area comprises structurally controlled topography with mesas and cuestas, developed on flat-lying or gently dipping Cretaceous sedimentary rocks: interbedded sandstone, mudstone, and shale. The sandstones are relatively resistant to erosion and underlie the uplands. The upland ground is flat and stable, but the slopes are undercut or over-steepened by mainstreams and have a high likelihood of rockslide initiation (Figure 1).

The plateau for the most part is heavily forested, but, along the Peace River, considerable areas, generally below 600 m, are flat or rolling and are only lightly forested. Much of this riverside country has been cleared and is under cultivation (Holland 1964).

The upland surface of the plateau is flat or gently rolling and stable. However, rock slopes along the mainstreams within the plateau have experienced frequent landslide activity. The major portion of the flat upland surface, moderately steep and steep slopes along the incised trunk streams, large deep-seated rockslides, and colluvial deposits or displaced rock blocks in the valley bottoms form specific landscapes in the Fort St. John Forest District (Figure 2). The study area discussed in this paper is located mainly along the valleys of the Halfway and Beatton Rivers and their main tributaries.

The plateau was glaciated during the Pleistocene. Ice from the Keewatin centre of accumulation moved southwest across the Alberta Plateau to the foothills and left a veneer of glacial till containing distinctive Keewatin boulders. After the maximum expansion of Keewatin ice and its retreat, piedmont and valley glaciers flowing eastward from the Rocky Mountains moved outward onto the plateau to leave moraines in a narrow belt along the eastern edge of the foothills (Holland 1964).

As the ice waned, channels discharged glacial meltwater into valleys, some of which were still blocked by ice. Thick sequences of glaciolacustrine mate-

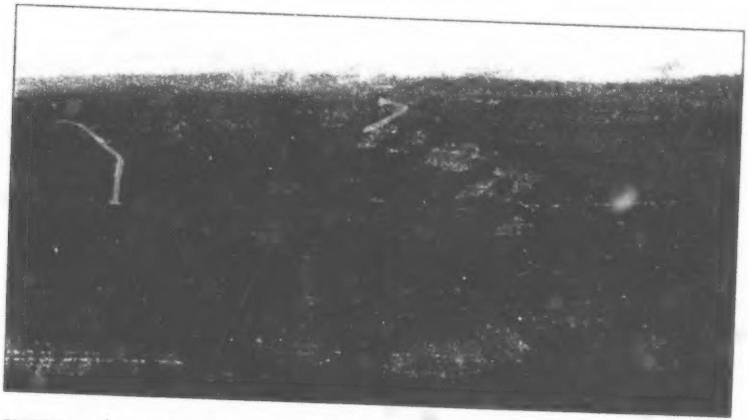


FIGURE 1 *An overview of a part of the upland surface of the Alberta Plateau in the Fort St. John Forest District.*

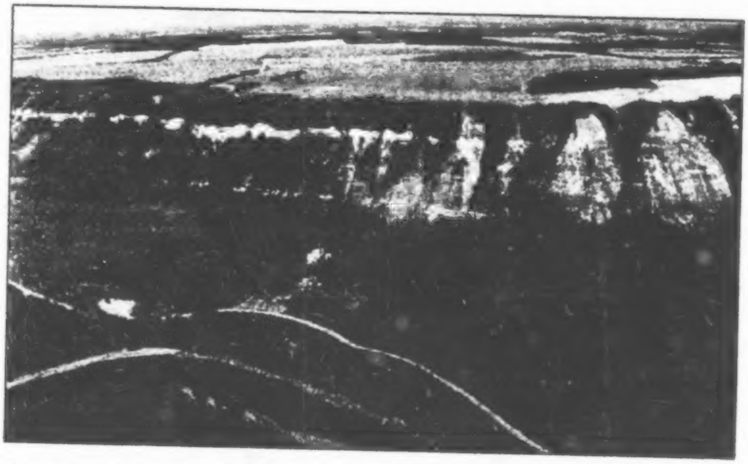


FIGURE 2 *An example of the flat terrain in the Halfway River valley, Fort St. John Forest District. Note the displaced materials below the main scarp—they are indicators of previous landslide activity.*

rials were deposited in ice-dammed lakes. The deep glaciolacustrine deposits that have been found along the main valleys, especially along the Peace River valley where large and deep-seated landslides have developed, are outside the scope of this paper.

The study area has a typically continental climate: long, cold winters and short summers with moderate precipitation. Mean annual temperature is about 1.3°C, with lower values on the slopes. Annual range of temperature is 33°C, only slightly less than the greatest range observed in Canada. Precipitation in the valleys averages 450 mm/yr, including 206 cm of snowfall. Weathering is very active, and is one of the important factors in bedrock decomposition process and landslide initiation.

This paper is based mainly on the data collected during several reconnaissance terrain mapping projects and terrain stability field assessments carried out in the study area in 1996 and 1997. The authors would like to emphasize that this paper focused on the landslide phenomena in Cretaceous sedimentary rocks in the study area, and their possible effects on forest management and the environment. Our nomenclature for the landslides follows Cruden and Varnes (1996).

BEDROCK GEOLOGY AND LANDSLIDE DEVELOPMENT

The rocks in the study area belong to the Fort St. John Group, comprising a thick sequence of shale with several sandstone members near the top; the Dunvegan Formation, which is a hard, cliff-forming sandstone; and the Smoky Group, comprising interbedded shale and sandstone. The rocks are flat-lying or gently dipping; consequently, extensive plateau areas and cuestas develop on the more resistant sandstone members. The interbedded shale is soft, more readily eroded, and widely underlying most of the lower areas of the Fort St. John Forest District.

The Peace River and its main tributaries, the Halfway and Beatton Rivers, control the drainage in the area. These rivers are incised into the soft Fort St. John shale. As a consequence, distinctive cuesta topography has been developed. The gentle slopes of cuestas generally face east and are structurally controlled by the gently east-dipping sandstone. A steep scarp slope faces west and falls away into a lower area underlain by Fort St. John shale.

Bedrock microstructures determine the main types of terrain stability problems in the study area. The gently dipping bedding planes, usually in the range of 5–15°, of the interbedded sedimentary rocks generally provide the major part of the surface of rupture for rockslides. Two to three sets of almost vertical or steeply dipping joints usually become lateral boundaries for these rockslides (Figure 3). All of these discontinuities provide the weaknesses for the occurrence of rockslides and cut the bedrock into large separate blocks.

River down-cutting plays a very important role in the initiation of these rockslides. These large deep-seated rockslides would not occur without the exposure of weak bedding planes along stream escarpments. The rockslides observed in the field are located on the banks along incised streams, and the main part of the upland surface remains stable. These features are obvious clues to recognize the importance of river down-cutting in landslide initiation in the area. When weak bedding planes are exposed at the toe of the slope, the rock mass separated from parent bedrock is ready to move out. Lateral erosion removes the last part of lateral support for the slope.

Groundwater is an important factor in the occurrence of the rockslides in the area. The shear strength on the bedding planes of shale and mudstone when fully saturated is reduced to almost the residual value, with no cohesion and a very low friction angle (as low as 5°).

Weathering processes, especially chemical weathering related to water

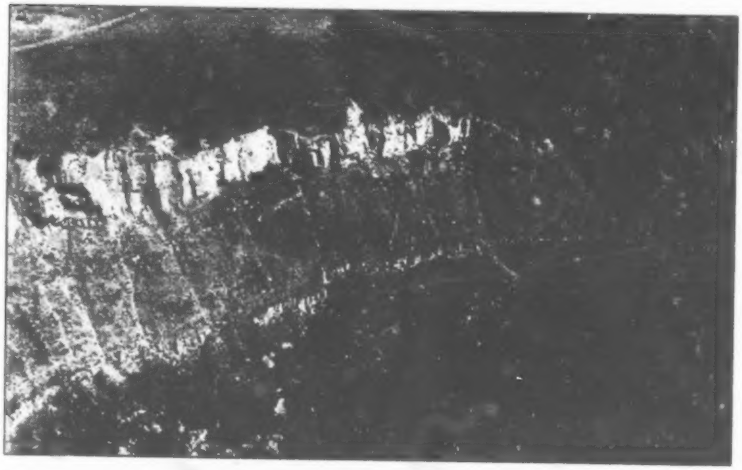


FIGURE 3 *A natural exposure of the interbedded sedimentary rocks in the study area. The thick sandstone layer forming the upland surface belongs to the Dunvegan Formation, whereas the rest of the rocks below belong to the Fort St. John Group. Note the gently dipping bedding planes and two sets of well-developed steeply dipping joints within the rocks. These joints provide the lateral boundaries for slope failures. Rock falls may also occur in thick sandstone layers on main scarps after a major movement event.*

percolation and tree root penetration, play a dominant role in rock decomposition. Decomposed shale and mudstone are more likely to absorb moisture and so reduce the strength of the rock mass.

CHARACTERISTICS OF LANDSLIDES IN THE STUDY AREA

The landslides we have found in the study area have the following distinctive characteristics.

The size of rockslides that have occurred in the Cretaceous sedimentary rock in the study area is typically large. Their dimensions usually reach 100 × 100 m in plan, with some up to 1000 × 1000 m (Figures 4–6). The depth of the main part of the rupture surface is in the range of 10–50 m. Volumes of these rockslides are in the range of 0.1–10 × 10^6 m^3. These large landslides have generally occurred on moderate (27–50%) to moderately steep

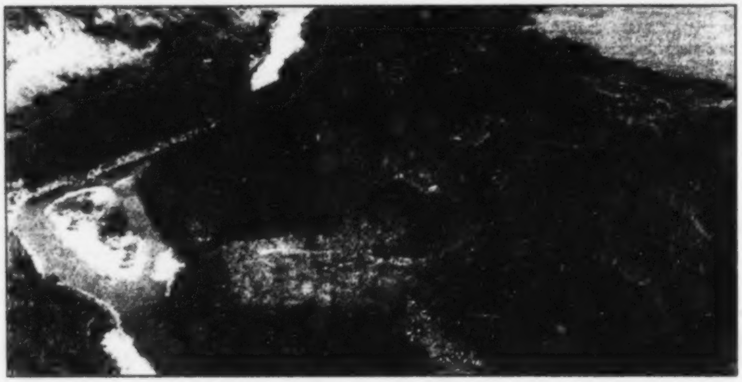


FIGURE 4 *An example of a rockslide in interbedded sedimentary rocks of Cretaceous age on the outer side of a river bend. The interbedded bedrock is clearly exposed on the main scarp.*

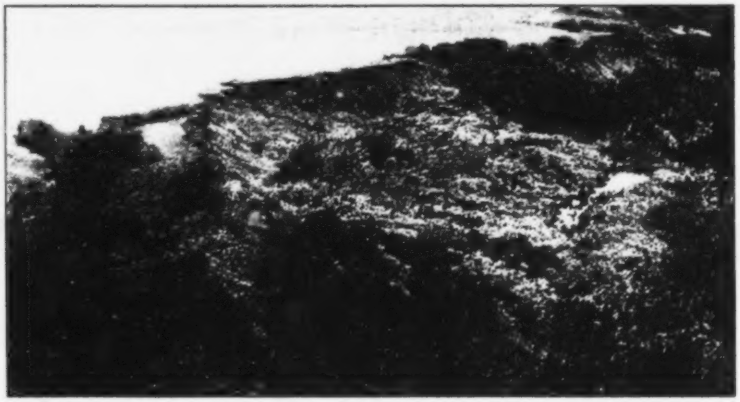


FIGURE 5 *Two large deep-seated rockslides in Cretaceous interbedded sedimentary rocks. Note the sag ponds on the right side of the photo indicating the movement of two separate blocks.*

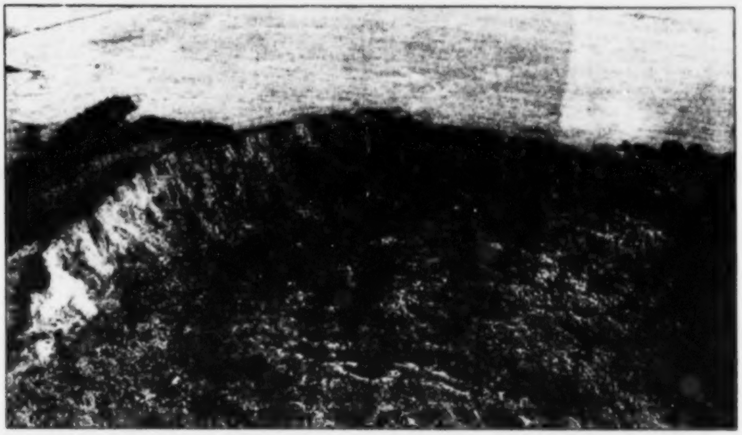


FIGURE 6 *A close view of the upper portion of the rockslide in Figure 5 gives some details of the main scarp area of the slide. Water comes from the crop field, the upland of the plateau, behind the scarp.*

(51–70%) slopes (Figures 5–7), with few examples on steep (> 70%) slopes (Figure 4). For example, the trees on the main body of the slide in Figure 7 are still upright and healthy, indicating that the main surface of rupture is deep and nearly horizontal. If the landslide is shallow, or tilted, and if the surface of rupture has a significant dip angle, the trees might have died.

The sag ponds in Figure 5 and the benches in Figure 7 indicate the retrogressive development of these landslides.

Generally, these landslides move slowly. However, some landslides in the area, for example the landslide in Figure 4, may move rapidly. From our experience, initial movement of the landslides in Figure 5 might have been rapid, based on the high main scarp and the obvious sag ponds, and they are moving slowly at present.

Figures 8 and 9 provide two additional examples of landslides in weathered Cretaceous sedimentary rocks. These landslides can occur in groups and have the potential to transform from rockslides to debris flows.

Almost all the landslides observed in the study area show an obvious tendency to move repeatedly. Identical interbedded sedimentary rocks and the same types of landslides were widely found in southwest China (Lu 1976, 1983). The observations carried out in exploration tunnels and the cores of drill holes in southwest China provide clues that the fines—clay and silt produced from broken shale and mudstone—are carried down by groundwater and accumulate at a relatively impermeable boundary to form a new zone of weakness. The displaced materials may move along the new zone of weakness again and again depending on the saturation of the fines. This hypothesis may also work in the Fort St. John Forest District. These landslides in the study area are very different from the landslides occurring in hard rocks—limestone, sandstone, and quartzite in the Rocky Mountains in both Alberta and British Columbia. The displaced materials derived from these hard rocks cannot move again because of the disappearance of the previous weakness zone and lack of enough fines to form a new weakness zone after the initial landslide event.

FIGURE 7 *Another large deep-seated rockslide in interbedded sedimentary rocks. Note that the slide occurred on a moderate slope. It provides a good example for estimating the low friction angle along bedding planes of the bedrock. It may be difficult to recognize such landslides within a cutblock in the central part of the slope.*

LANDSLIDES AND FOREST MANAGEMENT IN THE FORT ST. JOHN FOREST DISTRICT

The landslides observed in the study area may become another kind of problem to forest management. Most of them are large and deep-seated, and occur on moderate to moderately steep slopes. Some of these landslides are difficult to identify, especially at an early stage of development, by investigation carried out in a cutblock or small area. However, they may cause very serious impacts on the environment and damage to forest operations. Furthermore, as discussed previously, the upland surface of the plateau has only partly been dissected. Ongoing river erosion will continue to expose weak layers along valley escarpments, causing more of these kinds of landslides (Lu and Cruden 2000). We strongly recommend that detailed terrain stability mapping and terrain stability field assessments should be concentrated on the slope areas along deeply incised streams in the study area. In these areas, experienced terrain specialists should carry out detailed air photo interpretation and field assessment.

CONCLUSIONS

The major landslide types in Cretaceous sedimentary rocks in the Fort St. John Forest District are rockslides, rock falls, debris slides, and debris flows. The rockslide deposits and their weathering products tend to occur in groups, and may move again and again.

FIGURE 8 *Two neighbouring rockslides in weathered Cretaceous interbedded sedimentary rocks. They are almost identical in form, indicating that they have occurred under similar geological conditions.*

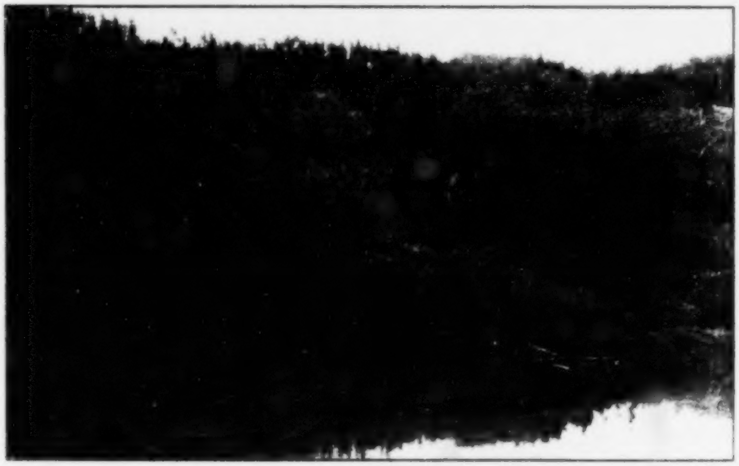


FIGURE 9 *A close view of the slide on the left side of Figure 8. Note that a rockslide occurred on the upper portion of the slope and the displaced materials flowed into the small river in the foreground.*

Surfaces of rupture of the rockslides in these Cretaceous rocks often follow gently dipping bedding planes, especially bedding planes in shale. The dip angle of major rupture surfaces can be as gentle as 5°. The boundaries of these rockslides generally follow steeply dipping joints.

River down-cutting plays a very important role in the initiation of these rockslides. The upstream retrogression of river down-cutting along the main tributary streams will continue to expose more and more weak shale bedding planes and cause more rockslides in the Fort St. John Group.

Groundwater and weathering processes have played an important role in the development of rockslides in the area by reducing shear strength along potential rupture surfaces.

Cretaceous interbedded sandstone, mudstone, and shale, and their weathering products, rank among the most landslide-prone materials in the Fort St. John Forest District. A clear understanding of the local geologic controls on landslide activity will enhance forest management in the district.

ACKNOWLEDGEMENTS

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REFERENCES

Cruden, D.M. and J.D. Varnes. 1996. Landslide types and processes. *In* Landslides: Investigation and mitigation. A.K. Turner and R.L. Schuster (editors). Transportation Res. Board, Washington, D.C. National Academy Press. Spec. Rep. 247:36–75.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. B.C. Dep. of Mines and Petroleum Resour., Victoria, B.C. Bull. No. 48.

Lu, Z. 1976. Investigation and control design for #377 landslide on the railroad from Chengdu to Kunming. Selected Papers on Landslides, China Railway Publishing House 1:108–14 (In Chinese).

———. 1984. Basic characteristics of landslide distribution and main types of landslides in China. Proc. 4th International Symp. on Landslides, Toronto, Ont. Can. Geotech. Soc. 1:411–8.

Lu, Z. and D.M Cruden. 2000. Fluvial processes and landslide activity in the western Peace River Lowland, Alberta, Canada. Proc. 8th International Symp. on Landslides, Cardiff, Wales. Thomas Telford, London, U.K. 2:955–60.

Displacement Behaviour of the Checkerboard Creek Rock Slope

THOMAS W.G. STEWART AND DENNIS P. MOORE

ABSTRACT

A slowly displacing rock slope, involving approximately 3 million m^3, located 1.5 km upstream of the Revelstoke Dam, in the Selkirk Mountains of British Columbia, has been the focus of a detailed investigation and slope monitoring program. The investigation and assessment have focused on the potential for a rapid slope failure that could cause a landslide-generated wave in the reservoir. Monitoring results indicate a seasonal pattern to the slow displacement process, beginning in the autumn when conditions are generally wetter, and continuing through the winter snowfall and snowmelt. During late spring and summer, very little displacement occurs. The monitored displacement behaviour provides some insight into the understanding of slowly deforming slopes, frequently described in the literature as mountain slope "creep" or "mass rock creep." Detailed numerical modelling studies have been carried out to investigate the current slope displacement behaviour, and have been used to estimate the impact of possible loading conditions, including the potential for rapid slope failure. A key factor in the assessment and prediction of slope behaviour is related to potential strength reduction in the rock mass due to weathering, ongoing slope displacement, or seismic loading. Strength reduction in the rock mass could potentially lead to the formation of a low-strength zone along which a rapid sliding failure could occur. Evolution towards this condition would be revealed by the instrumentation system, justifying the importance of continued slope monitoring. To fulfill this requirement, an Automated Data Acquisition System has been installed to provide real-time monitoring of slope conditions, and alarms have been installed to detect anomalous behaviour. However, this system is less likely to provide sufficient warning of a seismically triggered slope failure that could develop rapidly following a large earthquake.

INTRODUCTION

Slow displacements and a collection of slope deformation features outline a potential bedrock slide on the eastern slopes of the Columbia River valley, approximately 1.5 km upstream of the Revelstoke Dam (Figures 1 and 2). The potential slide has been referred to as the "Checkerboard Creek" rock slope, in reference to the drainage that runs along the eastern and southern sides of the potential slide area.

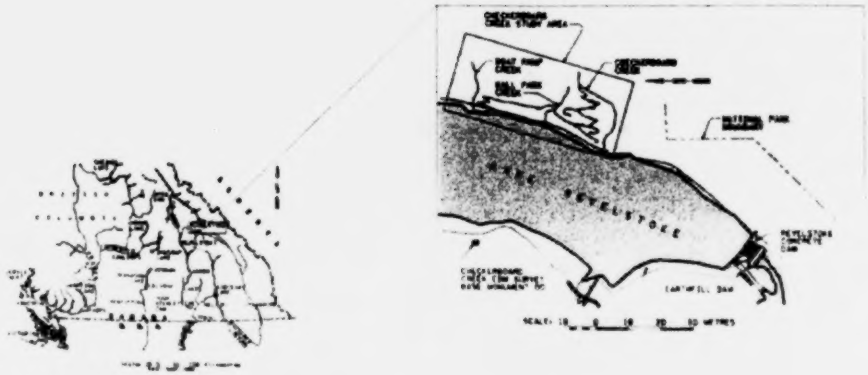
CHECKERBOARD CREEK STUDY AREA
CHECKERBOARD CREEK
LAKE REVELSTOKE
REVELSTOKE CONCRETE DAM
EARTHFILL DAM
SCALE 10 0 10 20 30 METRES

FIGURE 1 *Location plan.*

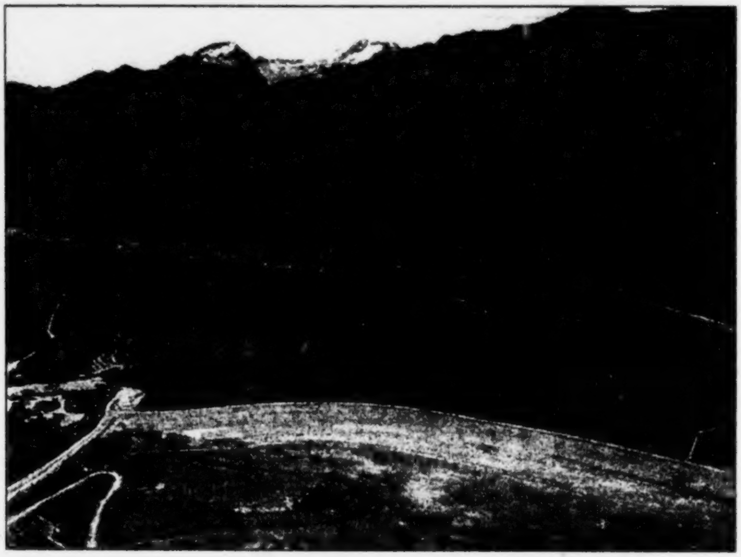

FIGURE 2 *Oblique view of slope. Checkerboard Creek enters reservoir at right of main rock cut in centre of photo. Main slope area is to left of creek. Note Revelstoke Dam (earthfill section) in foreground.*

Slope investigations were initiated in 1984 following the discovery of a network of apparently fresh tension cracks. The cracks are immediately uphill from a 70 m high excavation required for the relocation of a highway above the future level of Revelstoke Reservoir. The cracks were observed during reservoir slope inspections conducted in association with impoundment of the Revelstoke Reservoir. The initial surface monitoring network has been periodically upgraded and expanded in conjunction with ongoing investigations and inspections. Most recently, an Automated Data Acquisition System (ADAS) providing real-time monitoring has been installed. This paper presents an interpretation of the monitoring results and a discussion of the slope displacement behaviour to date.

SLOPE GEOLOGY

Bedrock is comprised primarily of massive to slightly foliated granodiorite and granite belonging to a tectonic slice of the Selkirk Allochthon referred to as the Clachnacudainn Salient. These rocks overlie the easterly dipping Columbia River fault, which has developed a broad, regional zone of altered and mechanically deformed rock (Lane 1984) that becomes progressively more pronounced with depth below the slope surface. The primary fault zones and related fabric dip easterly into the slope (Figure 3) and, based on slope displacement assessment and analyses, play an indirect role in the kinematics of the displacement process. Piezometric monitoring shows that the eastwardly dipping structures related to the Columbia River fault zone are low-permeability barriers to groundwater flow. They are considered to be barriers to infiltration, and to cause temporary perched groundwater conditions in the upper section of the rock mass where the slope displacement process is currently active.

Rock mass structure in the main slope area is dominated by two well-developed joint sets and the shear/fault zones previously described. The orthogonal joints dip steeply (> 80°), with the primary set generally parallel to the slope contours, and the secondary set striking perpendicular to the slope. The primary joint set exerts structural control on the tension crack development.

Rock mass quality is highly variable, ranging from very strong, fresh, undisturbed and blocky rock, to highly weathered and altered, weak and disturbed rock, containing frequent sheared and crushed zones. Typically, the poor-quality rock is localized within 60 m of the slope surface, where active displacements have been monitored. The underlying rock is generally fair to good in quality, with localized zones of poor rock along shear zones.

GEOMORPHOLOGY

Conspicuous slope features include a series of open tension cracks and partially infilled bedrock linears oriented sub-parallel to the topographic contours. The open tension cracks are exposed in the central slope area between 650 and 740 m elevation (Figure 4) and are seen as discrete, planar to sinuous bedrock cracks in outcrop, and as collapse features where the cracks are covered by thin surficial deposits. The bedrock walls of the open tension cracks show no signs of glacial erosion, which distinguishes them from the infilled linears and indicates that opening of the tension cracks is post-glacial.

Infilled linears on the slope appear as wide (up to 15 m) gullies, benches, and subtle uphill-facing scarps. These features were partially obscured by logging activities during the 1950s. Trenching of these features indicates that bedrock has been glacially scoured along zones of weakness, including faults, shears, and fracture zones, with subsequent infilling by glacial and colluvial deposits. Post-glacial offset in the overburden deposits of up to 25 cm has been observed. Linears with a similar morphology to those at Checkerboard are found throughout this reach of the Columbia River valley and British Columbia, and in many other mountainous regions of the world (Stewart 1997). Numerous studies (Tabor 1971; Radbruch-Hall et al. 1977; Bovis and Stewart

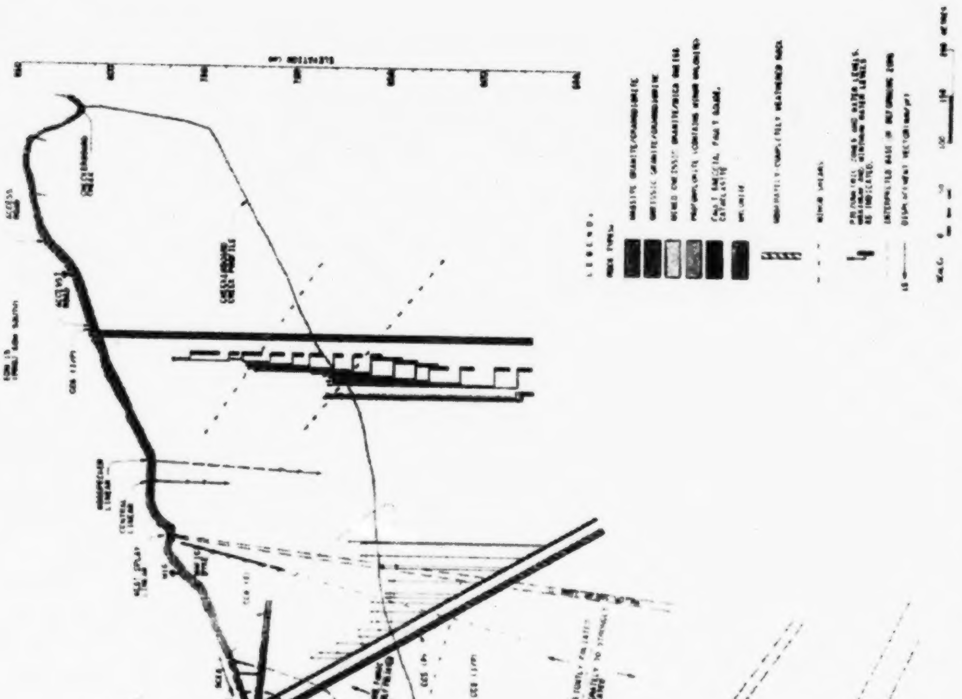
INTERPRETED ACTIVE MOVEMENT ZONE
LEGEND

FIGURE 3 *Slope cross-section showing geology, groundwater, instrumentation, and displacement zone.*

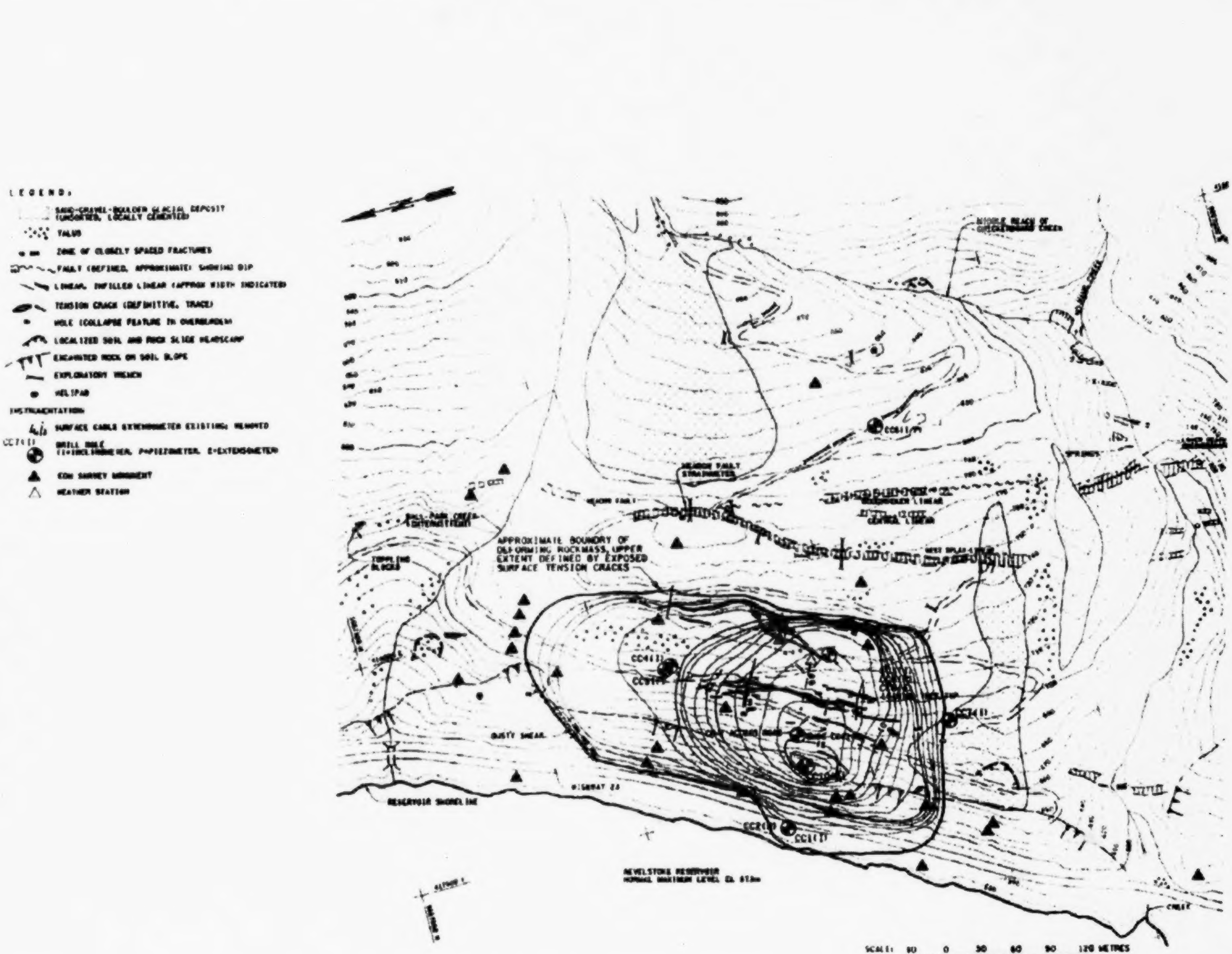
LEGEND:
SAND-GRAVEL-BOULDER GLACIAL DEPOSIT (UNSORTED, LOCALLY CEMENTED)
TALUS
ZONE OF CLOSELY SPACED FRACTURES
FAULT (DEFINED, APPROXIMATE) SHOWING DIP
LINEAR, INFILLED LINEAR (APPROX WIDTH INDICATED)
TENSION CRACK (DEFINITIVE, TRACE)
HOLE (COLLAPSE FEATURE IN OVERBURDEN)
LOCALIZED SOIL AND ROCK SLIDE HEADSCARP
EXCAVATED ROCK OR SOIL SLOPE
EXPLORATORY TRENCH
HELIPAD
INSTRUMENTATION
SURFACE CABLE EXTENSOMETER EXISTING; REMOVED
CC7(I)
DRILL HOLE (I=INCLINOMETER, P=PIEZOMETER, E=EXTENSOMETER)
EDM SURVEY MONUMENT
WEATHER STATION
APPROXIMATE BOUNDRY OF DEFORMING ROCKMASS, UPPER EXTENT DEFINED BY EXPOSED SURFACE TENSION CRACKS
TOPPLING BLOCKS
DUSTY SHEAR
HIGHWAY 23
RESERVOIR SHORELINE
REVELSTOKE RESERVOIR NORMAL MAXIMUM LEVEL EL 573m
CC4(I)
CC1(I)
CC2(I)
MIDDLE REACH OF CREEK
CREEK
SCALE: 30 0 30 60 90 120 METRES

FIGURE 4 *Plan of slope, illustrating slope displacement features, instrumentation, and displacement rate contours.*

1998) have suggested a slope deformation origin for these features; however, evidence at Checkerboard Creek suggests an origin related to both erosional and gravitational effects.

Another significant geomorphic feature is the locally steeper topography in the central area of the slope below the current reservoir level (573 m elevation). This local steepening could have been caused by fluvial erosion of the Columbia River, which flowed along an easterly meander below the central portion of the slope. Alluvial fans limited this erosion at the north and south ends of the main slope area. This active fluvial undercutting could have contributed to the slope displacement process.

SLOPE INSTRUMENTATION

The slope is monitored by an array of instruments installed between 1984 and 2000, including: electronic distance measurement (EDM) surveys, borehole and surface cable extensometers, inclinometers, time domain reflectometry (TDR) cables, a three-dimensional strain gauge, piezometers (standpipe and Multiport types), a weather station, and ADAS equipment (Figure 4).

This instrumentation network has been established to develop a comprehensive understanding of the slope displacement behaviour and the hazard associated with potential slope failure; and to provide an early warning system for detecting potential evolution of the slow displacement process into a rapid failure.

Instrumentation results have indicated a complex slope behaviour pattern, requiring several years to manifest, due principally to the very slow displacement rates of 5–15 mm/yr. The slope conditions and displacement behaviour, discussed in the following sections, are an assessment of present-day behaviour, and should be considered in perspective with the interpreted long history of displacement at Checkerboard Creek.

CLIMATIC CONDITIONS

Air temperatures range from –25° to 35°C, with freezing conditions typically prevailing from late November through March. Annual cumulative precipitation is typically 1500–2000 mm, with about 40% falling during October–January, related to regional Pacific storm systems.

GROUNDWATER CONDITIONS

Slope groundwater conditions are based on the results of piezometric profiling during drilling, piezometric monitoring, and general observations during slope mapping and inspections.

Piezometric profiling and piezometer records reveal numerous, discrete pore pressure differences of ≤ 40 m across short lengths of the drillholes (Figure 3). This indicates a compartmentalized groundwater regime in the slope, related to the low-permeability shear zones.

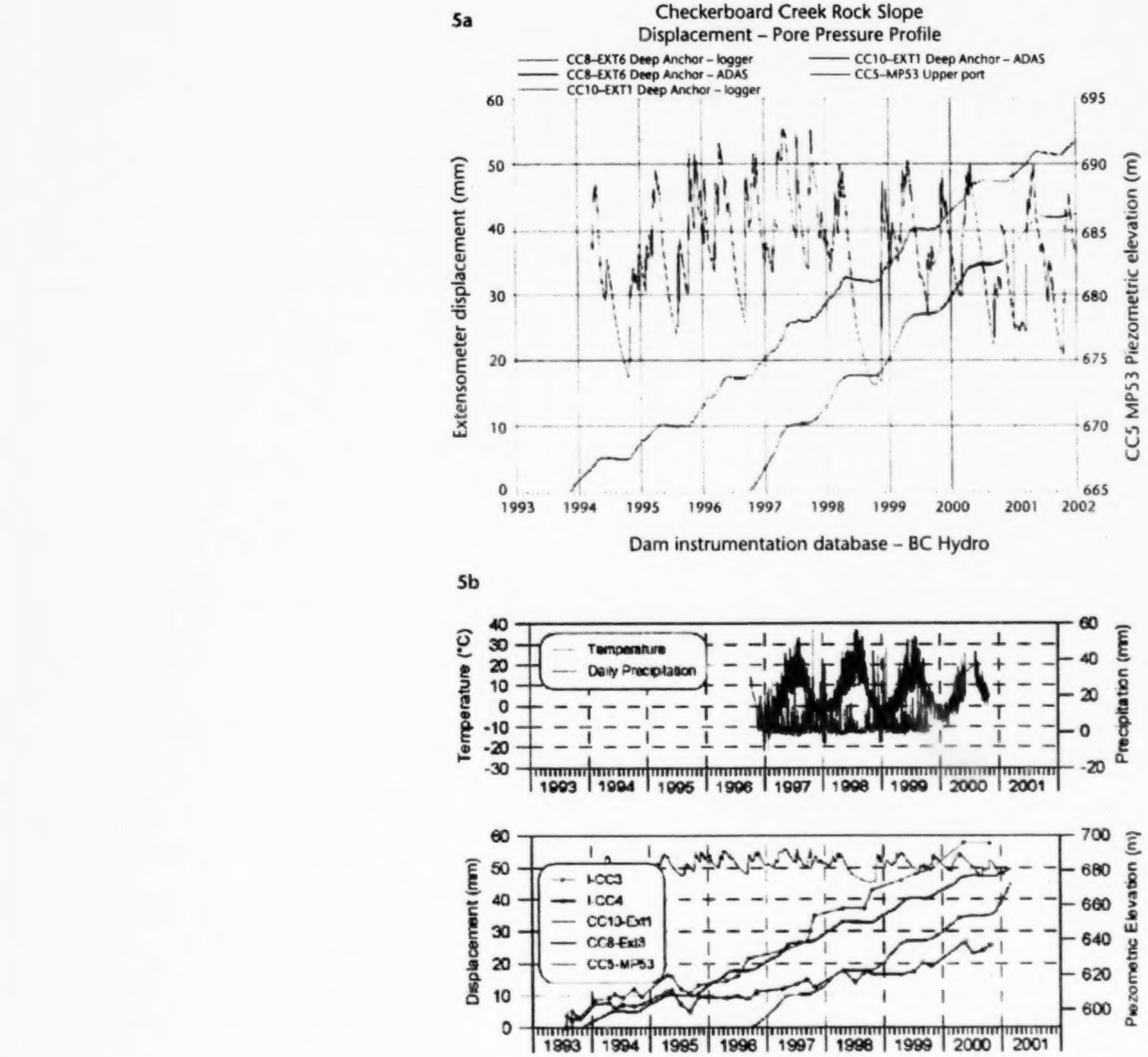

FIGURE 5 *(a) Plot of slope displacement and piezometric pressure for the period 1993–2002. (b) Plot of slope displacement, piezometric pressure, and precipitation, illustrating the relationship between piezometric fluctuations and slope displacement.*

Piezometric monitoring has indicated that continuously saturated conditions exist 50–80 m below the slope surface (Figures 3 and 5), which is below the base of the active slope displacement zone. Seasonal piezometric variations of ≤ 20 m occur, are greatest towards the top of the continuously saturated rock mass, and progressively diminish with depth below the slope surface.

Monitored piezometric levels have displayed a direct response to precipitation, and to a lesser degree, seasonal snowmelt. Piezometric increases in the upper monitoring zones typically display a 12- to 18-hour time lag following significant precipitation, with a progressively longer time lag noted with increasing depth below the slope surface. Moreover, the magnitude of piezometric response to precipitation and infiltration/recharge is progressively smaller with increasing depth below the slope surface. These conditions indicate that the piezometric fluctuations are dominated by local infiltration, rather than by regional flow.

Piezometric levels display sharp increases associated with autumn-winter precipitation and spring snowmelt, followed by a general decreasing trend during spring to early autumn. Transient groundwater flow and pressures are interpreted to develop, particularly in the upper compartmentalized zones of the rock mass, and are considered to act as a trigger for the seasonal slope displacement cycles, based on the concurrence of increasing piezometric levels and the initiation of accelerated slope displacements.

Relative to the main slope area, the Checkerboard Creek channel has topographically downcut 80–90 m, and is topographically lower than borehole piezometric levels (Figure 3). Consistent seepage from the side walls of the creek channel has been observed. In contrast, seepage has generally not been observed on the exposed highway excavation, except during very short periods following seasonal snowmelt. These observations indicate that general slope groundwater flow is likely towards the creek channels (north/south), and not directly downslope (west). Moreover, these observations are consistent with the notion of compartmentalized groundwater, perched above and behind major geologic structures that impede downslope groundwater flow and sustain significant downslope groundwater gradients.

DISPLACEMENT BEHAVIOUR

Discussion of slope displacement behaviour focuses on the more reliable and accurate subsurface instruments. Surface monitoring results have been instrumental in establishing general displacement trends and areal displacement patterns, and serve to confirm observations in the subsurface instruments.

Subsurface slope displacements have been identified in inclinometer casings CC1, CC3, and CC4 to date, but not in CC6 and CC7. CC6 and CC7 thus provide easterly and southerly limits on the area of displacement, respectively.

The inclinometers indicate that displacements occur to depths of 50–55 m in the rock mass, with the following characteristics:

- Generally, the downslope displacement occurs diffusely throughout the rock mass, with the result that the surface moves more relative to the rock at depth, causing an overall downslope rotation (toppling).

- In CC3, an 8–10 m wide zone at the base of the displacing mass accommodates a considerable portion of the observed deformation (Figure 3); displacement below this zone appears insignificant.
- An overlying and relatively narrow zone, which indicates a reverse sense of displacement from adjoining zones, shows a relative "upslope" displacement direction, and is considered characteristic of a "toppling" deformation mechanism.

Thus, inclinometer data have revealed the slope movements to be characterized by a general downslope rotation (toppling) rather than block sliding or rotation along a continuous failure plane, an observation consistent with the observed drill core and surface geomorphology.

Displacements of 2 mm/yr in inclinometer CC1 indicate that slope displacement may extend below the level of Highway 23. These could be either an extension of the slope displacement recorded in the upper area, or a localized slope process below the level of the highway, independent of the larger upslope instability. A projection of the interpreted displacement zone from all slope instruments (Figures 3 and 4) suggests the former.

The most detailed record of slope displacement has been obtained from two multi-point borehole extensometers that monitor conspicuous surface tension cracks. These 60 m long sub-horizontal instruments provide a nearly continuous record of slope displacement, described as follows:

- Average annual displacements are 5–15 mm, occurring exclusively during an "active" phase from October to April of each year. Between May and September of each year, essentially no displacement has been recorded to date (Figure 5a).
- Subsurface thermistors have recorded insignificant temperature fluctuations in the rock mass. Assessment of thermistor and surface climatic information has indicated that slope displacement is not explained by temperature effects alone.

DISCUSSION OF DISPLACEMENT BEHAVIOUR

Slope monitoring since 1984 has revealed very slow displacements, with average downslope rates of 5–15 mm/yr. Monitoring has revealed a clear seasonal pattern to this movement, dominated by an active phase occurring in the late autumn to late winter, and a relatively inactive phase during the spring to late autumn period (Figure 5a). Careful scrutiny of the borehole extensometer records indicates distinctive variations in displacement rate, particularly during the "active" winter phase (Figure 5b). Sharp piezometric increases related to surface groundwater recharge from precipitation and/or snowmelt apparently trigger these accelerated displacement responses. Conversely, periods of prolonged piezometric level decrease, typical during summer to autumn, correlate with cessation of the displacements.

There does not appear to be a "threshold" precipitation or piezometric level required to initiate accelerated slope displacement. Isolated, high-volume precipitation during the May to September period has not initiated slope displacements, whereas more prolonged, but smaller-magnitude events in the October to April period typically initiate accelerated slope displacements. In terms of piezometric levels, accelerated displacements can be triggered by lower, but rising, piezometric levels, compared with higher, but falling, piezometric levels when slope displacements decelerate.

Inclinometer records also support the seasonal slope displacement cycles and relationship to increased piezometric levels and associated transient groundwater pressures. Initial displacement direction in each annual cycle is closely perpendicular to the strike of the primary discontinuities, up to 20° oblique to the downslope direction. Association of inclinometer displacement and increased piezometric pressures suggests a reduction in effective rock mass stresses leading to joint dilation and slip. Subsequent inclinometer displacements indicate a transition towards the downslope (gravitational) direction. As slope displacements decelerate with piezometric "discharge," the inclinometers have indicated a minor upslope "rebound," which again trends perpendicular to the primary discontinuity set.

The inclinometer profiles in CC3 and CC4 indicate that the displacement mechanics are governed by an overall downslope rotation, characterized as "toppling" along the steeply dipping discontinuities, with displacement rates greatest at the slope surface and progressively diminishing with depth (Figure 3). This observation is consistent with the array of surface tension cracks and absence of a through-going basal sliding surface.

The average annual rate of displacement has remained relatively uniform since 1984. To account for the widths of the tension cracks, similar slope displacements would have to have been active for at least hundreds of years, and more likely throughout much of the Holocene. Observations supporting this include the span of individual tension cracks (up to 4 m), the cumulative span across tension cracks in the central section of the slope (~10 m), large trees growing in the tension cracks, infilling deposits observed near surface and at depth in the tension cracks, and weathering and organic growth (moss/lichens) on the tension crack walls.

During excavation of the highway rock cuts in 1977/78, considerable backbreak of the designed rock cut benches occurred, which was attributed to the locally, highly weathered nature of the rock. Retrospectively, the excavation difficulties are interpreted to be indicative of the marginal slope stability conditions and the existence of a slow, active slope displacement process. Instrumentation data indicate that any remnant slope displacement triggered by the excavation had abated sometime prior to monitoring, based on the inactive displacement behaviour noted during subsequent summer periods. This does not imply that the highway excavation had no effect on the stability of the slope, only that any accelerated displacements that might have been triggered by that change are no longer apparent, as evidenced by the apparently inactive displacement behaviour in the summer periods.

Clear evidence from instrumentation data indicates that current slope displacement behaviour at Checkerboard Creek is not a remnant creep effect from either prehistoric causes or the recent highway excavation, but is related to the elevated groundwater conditions that prevail in the upper section of the rock mass during the winter months.

The current slope displacement process and the implications of slope failure highlight the importance of maintaining a comprehensive monitoring system, regular inspections, and ongoing, careful analysis of all instrumentation results. These activities are essential for developing a clear understanding of the slope behaviour and the related hazard of a landslide wave, and to detect any changes in slope displacement behaviour.

ANALYTICAL STUDIES

Numerical modelling studies using the computer code FLAC were carried out to forecast potential seismic and groundwater loading conditions. FLAC, based on an incremental finite difference approach, provided the capability to model displacements and the complex deformation process. Application of a limit equilibrium modelling approach was not considered appropriate, based on the lack of a basal sliding mechanism. Material properties for the model were based on the results of core logging observations and measured parameters, and compressive strength testing. This information was incorporated to establish rock mass and discontinuity properties, based on the Hoek and Brown (1997) and Bandis (1993) empirical approaches, respectively.

The results of the seismic analyses indicated the following:

- A simulated 1-in-1000-year seismic event (0.1 g) would generate displacements of less than 50 cm, which would not likely trigger slope collapse.
- Conversely, the 1-in-10 000-year seismic event (0.2 g) indicated displacements in excess of 10 m, which would be more likely to trigger slope collapse.

Investigation of groundwater conditions using FLAC indicated the following:

- Reservoir filling had no significant effect on the slope stability.
- A 50-m rise in the level of the continuously saturated rock mass above currently recorded levels would be required to cause slope collapse.
- A state of constant slope recharge and rising piezometric levels could generate significant downslope displacements, potentially leading to slope collapse.

Modelling of the long-term slope behaviour indicated that current displacements in the order of 5–15 mm/yr are likely to persist, provided that groundwater conditions continue to trigger the displacement cycles. The current, slow displacement process is forecasted to prevail until cumulative displacement potentially reduces overall rock mass strengths to levels that allow a change in deformation mechanics. In the absence of large seismic shaking, a change in slope displacement behaviour due to strength reduction is likely to provide indications that would be identified in the instrumentation network in the form of changing displacement rates and patterns.

SUMMARY

Displacement behaviour in the Checkerboard Creek rock slope is summarized as follows:

- About 3 million m^3 of rock is currently involved in a very slow, complex displacement process. Monitored displacements are greatest along the slope surface, progressively diminish with depth, include some zones of concentration, and are not detected below a depth of about 55 m.

- The interpreted displacement mechanism involves a complex interaction of dilation and slip along steeply dipping discontinuities, with offset across intersecting structures, resulting in a displacement profile characterized by overall downslope rotation of the deforming rock mass.
- Monitored displacements are spatially non-uniform across the slope surface, displaying an increase towards the centre of the mass, immediately above the highway cut.
- Displacements from 1993 to 2000 have indicated a seasonal pattern, comprising an "active" period between October and April, and an "inactive" period between May and September. Average downslope displacement rates range from 2 to 15 mm/yr, but occur almost entirely during the active period. The active period indicates the marginal stability of the rock slope.
- The observed seasonal displacement pattern clearly correlates with climatic conditions involving increased precipitation and infiltration during the active period. Slope displacements are interpreted to be primarily driven by transient groundwater conditions that develop above the long-term phreatic surface during periods of significant infiltration.
- Numerical modelling studies, using the computer code FLAC, have indicated that a significant increase in the long-term phreatic surface, some 50 m above currently recorded levels, would be required to cause slope collapse; such a scenario is considered highly unlikely.
- A condition of constant slope recharge and increasing piezometric pressures within the displacing mass could generate significant downslope movements, and could lead to slope collapse.
- Gradual degradation of the rock mass quality is expected to continue with ongoing slope displacement. Previous deterioration is seen in the drill core, and is largely confined in the currently displacing mass.
- Dynamic numerical modelling studies of the rock slope have indicated that seismic loading corresponding to the 1-in-10 000-year event, in conjunction with active period transient groundwater conditions, generates slope displacements of up to tens of metres and appreciable downslope velocities, which could lead to slope collapse.
- Reduction of the transient groundwater pressures may be a potentially effective measure in reducing slope displacements, and the risk of a seismically triggered collapse.

Possible remedial options are under consideration. In the meantime, a comprehensive ADAS with real-time monitoring and integrated alarms has been installed and is carefully monitored.

ACKNOWLEDGEMENTS

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REFERENCES

Bandis, S.C. 1993. Engineering properties and characterization of rock discontinuities. *In* Comprehensive rock engineering, principles and practice. J.A. Hudson (editor). Pergamon, Oxford, U.K. Vol 1., pp. 155–84.

Bovis, M.J. and T.W. Stewart. 1998. Long-term deformation of a glacially undercut rock slope, southwest British Columbia. *In* Proc. 8th IAEG Conf. D.P. Moore and O. Hungr (editors). Vancouver B.C., Sept. 21–25, 1998, Balkema, Rotterdam, Netherlands. Vol. II, pp. 1267–76.

Hoek, E. and E.T. Brown. 1997. Practical estimates of rock mass strength. Int. J. Rock Mech. Min. Sci. 34(8):1165–86.

Lane, L.S. 1984. Brittle deformation in the Columbia River fault zone near Revelstoke, southeastern British Columbia. Can. J. Earth Sci. 21:584–98.

Radbruch-Hall, D.H., D.J. Varnes, and R.B. Colton. 1977. Gravitational spreading of steep-sided ridges ("Sackung") in Colorado. J. Res. U.S. Geol. Survey 5:359–63.

Stewart, T.W. 1997. Investigation of rock slope deformation at the Wahleach hydroelectric project using the FLAC computer code. M.A.Sc. thesis. Univ. B.C., Vancouver, B.C.

Tabor, R.W. 1971. Origin of ridge-top depressions by large-scale creep in the Olympic Mountains, Washington. Geol. Soc. Am. Bull. 21:1811–22.

Forestry on Fans: Identifying Hydrogeomorphic Hazards

DAVID WILFORD, MATT SAKALS, AND JOHN INNES

ABSTRACT

For forest managers, fans pose a serious problem in mountainous areas due to periodic debris flows, hyperconcentrated flows, and peak flows. These hydrogeomorphic events challenge roads and drainage structures, impact plantations, and pose safety risks. In addition, natural events can be aggravated by forestry activities on fans, impacting aquatic resources, improvements, private property, and drinking water. This paper presents first-year results from a research project that is developing a hazard classification for forestry on fans and documenting past forest management experiences on fans. The study area is in the Prince Rupert Forest Region of British Columbia. The hazard classification will be based on a combination of site features on fans and watershed attributes. Central to the site features are forest stand attributes that, in combination with dendrochronology, are used to determine the power and frequency of hydrogeomorphic events. Other site features include geomorphic and sedimentologic signatures. Watershed attributes include morphometrics, extent of unstable terrain, channel characteristics, and snow avalanches. The documentation of past forest management experience highlights the need to recognize fans early in the planning process, recognize evidence of hydrogeomorphic processes, modify current road construction prescriptions, and expand the recognition of riparian forests from their current fish focus to include their hydrogeomorphic role. Alluvial and colluvial fans are the products of unstable terrain and can be subject to contemporary hydrogeomorphic processes. Recognition of these hazards is a key to sustainable forest management in mountainous areas.

INTRODUCTION

Fans are gently sloping landforms in mountainous areas that present an enticing opportunity for a range of land uses from forestry to housing developments. However, floods, hyperconcentrated flows, and debris flows—the processes that form fans—frequently challenge development. Natural events have been aggravated by forestry activities, exacerbating impacts to fish habitat, private property, improvements, and drinking water.

The current lack of a hazard classification for forestry on fans has led to a failure to recognize the presence of hydrogeomorphic processes and, consequently, impacts to roads, drainage structures, plantations, and safety issues. Operational forestry staff are sometimes surprised when they encounter challenges on fans, particularly in situations where the area has been mapped for terrain stability hazards using the current standards adopted in British Columbia (B.C. Ministry of Forests 1999). This is because the current hazard maps focus primarily on identifying initiation zones, rather than runout zones, which are frequently fans.

A fan is a landform, the surface of which forms a segment of a cone that radiates downslope from the point where a stream emerges from the confines of a mountain channel (Bull 1977; Ritter et al. 1995). Fans are composed of sediments that originate in a source area watershed and are transported by fluvial processes or debris flows, or a combination of the two. Alluvial fans are characteristically < 4° (Jackson et al. 1987). Debris flow fans are steeper—to 15° using the British Columbia terrain system (Howes and Kenk 1988) or 20° using the international system (Bull 1977). Steeper fans are usually referred to as cones.

The origin of many fans in British Columbia is linked to glacial episodes unrelated to modern conditions (Ryder 1971a, 1971b; Ritter et al. 1993). However, there is a spectrum of fans ranging from actively growing, and dissected, to those in a steady-state, dynamic equilibrium (as described in other environments by Denny 1965, 1967; Hunt and Mabey 1966; Hooke 1968; Beaty 1970). The contemporary activity may be superficial given the overall thickness of a fan; however, such activity can have significant implications for forests, roads, drainage structures, and plantations.

This paper describes a research project that is using site and watershed features to develop a hazard classification for forestry activities on fans. Literature explicitly regarding fans is heavily biased to arid regions and very limited information exists regarding the hydrogeomorphic role of forests on fans. We are using knowledge from a range of related subject areas because there is a considerable body of literature on debris flows (Costa and Wieczorek 1987), floods (Baker et al. 1988), and dendrochronology and forest stand development (Oliver and Larson 1996).

Fieldwork began in the spring of 2000 in the Prince Rupert Forest Region, British Columbia. While the hazard classification has not yet been finalized, extension of initial results to operational activities has clearly demonstrated that there is both an interest and an opportunity to improve the nature of forestry activities on fans.

A BRIEF DESCRIPTION OF THE STUDY AREA

The study area is in west-central British Columbia, within the Prince Rupert Forest Region (Figure 1). Study fans lay across a broad geographic area, between 53°46′ and 55°43′ N and 126° and 129°10′ W.

The western fans are within the Coastal Western Hemlock (CWH) biogeoclimatic zone and their watersheds have Mountain Hemlock (MH) and Alpine Tundra (AT) at higher elevations (Banner et al. 1993). The central fans are within the Interior Cedar–Hemlock (ICH) biogeoclimatic zone and their watersheds have Engelmann Spruce–Subalpine Fir (ESSF) and Alpine Tundra (AT) at higher elevations. The eastern fans are within the Sub-Boreal Spruce biogeoclimatic zone and their watersheds have ESSF and AT at higher elevations. Some of the eastern fans are totally within the ESSF. Major tree species found on fans are presented in Table 1.

The study area lies within the Western and Interior Systems of the

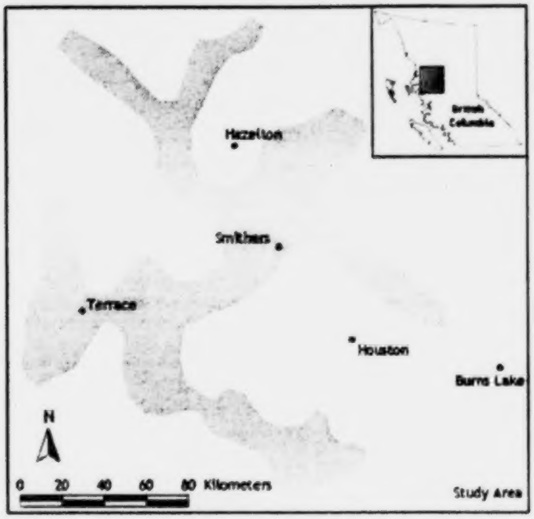

FIGURE 1 *Location map of the study area.*

TABLE 1 *Major tree species on the study area fans. Hybridization between the spruce are common in the study area (Coates et al. 1994).*

Common name	Latin name
White spruce	*Picea glauca*
Engelmann spruce	*Picea engelmannii*
Sitka spruce	*Picea sitchensis*
Western hemlock	*Tsuga heterophylla*
Western redcedar	*Thuja plicata*
Lodgepole pine	*Pinus contorta* var. *latifolia*
Amabilis fir	*Abies amabilis*
Subalpine fir	*Abies lasiocarpa*
Paper birch	*Betula papyrifera*
Cottonwood	*Populus balsamifera* ssp. *trichocarpa*
Aspen	*Populus tremuloides*
Red alder	*Alnus rubra*
Mountain alder	*Alnus incana*

Canadian Cordillera (Holland 1964). The Kitimat Ranges are within the Coast Mountains of the Western System. They are granitic mountains, characteristically round-topped and domed because they were overridden by glacial ice. The Interior System includes the Skeena Mountains, Nass Basin, Hazelton Mountains, and Nechako Plateau. This system is underlain chiefly by volcanic and sedimentary rocks and overall is less rocky and rugged than the Western System.

Long-term climatic stations in the study area are limited to valley-bottom locations. Extrapolation of records to study watersheds can be problematic due to mountainous terrain. However, this information can provide an indication of extreme events even though the absolute amounts of precipitation may be uncertain. Septer and Schwab (1995) compiled a record of floods for the Prince Rupert Forest Region. The records include data from the long-term stations plus newspaper reports and records from the Hudson Bay Company.

The Water Survey of Canada operates a series of stream gauging stations in the study area. However, most gauged watersheds are very large compared with the study watersheds, making unit runoff calculations and even event dating problematic. However, the hydrometric data are useful in describing the principal runoff regimes. Characteristically, the western and central portions of the study area experience biannual peak flows. Spring snowmelt provides the highest volume of runoff, and in some years the highest peak flows. Fall rain or rain-on-snow events can produce significant peak flows as well as erosion events (debris avalanches and debris flows). The same biannual peak flows occur in the eastern portion of the study area; however, in general, the spring snowmelt peaks are significantly larger than the fall peak flows.

METHODS

For this project, we are defining "contemporary" as within the last 300–500 years. The reason for this time frame is its relevance to forestry and our principal dating mechanism, dendrochronology. The term "hydrogeomorphology" refers to a combination of hydrologic and geomorphic processes, namely debris flows, hyperconcentrated flows, floods, channel avulsions, and snow avalanches.

One objective is to describe 60 fans and their watersheds: 30 that are forested and 30 that have been harvested or roaded. In each case, the fans will range from stable to actively influenced by hydrogeomorphic processes. Field descriptions of fans include forest stands, biogeoclimatic zones, hydrogeomorphic processes (Table 2), dendrochronology, stream channels, and topographic cross-sections. On those fans with forestry activities, field descriptions are supplemented with a history compiled through discussions with operational staff and pre-logging air photos and forest cover maps.

Reconnaissance overviews of watersheds are undertaken by helicopter to describe stream channels, sediment sources, and snow avalanche activity. On the ground, three aspects of hydrogeomorphic events are described: frequency, power, and extent of disturbance. Frequency is established using dendrochronology (dating of scars, abrupt changes in radial growth, physiological features, and tree establishment). Four time classes were defined that are relevant for forestry (Table 3). The selection was based on B.C. Forest Practices Code requirements (free growing, road drainage structures), forest rotations, and the spectrum of forestry plans (from development plans to Land and Resource Management Plans).

The power of events is assessed based on the impact to a forest stand (Table 4). The classes have direct implications for forestry investments. For example, low-power events may have impacts on newly established regeneration but should have limited impacts on sapling-sized regeneration. Moderate-power events may remove trees that are younger than 50 years old, and thin older stands. Moderate-power events may have some effect on roads and drainage structures. High-power events will remove trees and drainage structures and cause significant damage to roads.

The extent of impact from events is determined through dendrochronological observations, establishment of younger cohorts, and other physical observations (e.g., tree burial, sediment storage behind logs [log steps], fine sediments on vegetation, levees, and boulder/gravel splays).

TABLE 2 *Classification and characteristics of flow processes and deposits (after VanDine 1985; Smith 1986; Pierson and Costa 1987; Wells and Harvey 1987; Costa 1988)*

Characteristics	Water flood	Hyperconcentrated flow	Debris flow
1. Flow			
Flow type	Fully turbulent	Partly turbulent (at all times, however, high *sediment load dampens* small eddies) to laminar	Laminar at time of deposition but may be turbulent on steep slopes
Mean velocity	To 90 km/hr	0.6 m/min to 115 km/hr	To 115 km/hr
Sediment concentration	1–40% by weight 0.4–20% by volume	40–70% by weight 20–47% by volume	70–90% by weight 47–77% by volume
Sediment support mechanism	Turbulence, electrostatic forces	Turbulence, grain dispersive pressure, buoyancy	Matrix strength (cohesion and structural support), grain dispers. press., buoyancy
Sediment concentration profile	Non-uniform (solids and water are separate components of flow)	Non-uniform to uniform (solids and water are separate components of flow)	Uniform (solids and water move as a single viscoplastic body)
Bulk density	1.01–1.33 g/cc	1.33–1.80 g/cc	1.80–2.30 g/cc
Shear strength	0–100 dyne/cm^2	100–400 dyne/cm^2	> 400 dyne/cm^2
Fluid type	Newtonian	Newtonian to Non-Newtonian	Non-Newtonian Viscoplastic (coulomb-viscous and Bingham-plastic models)
Viscosity	0.01–20 poise	20– 200 poise	>> 200 poise
Fall velocity (% of clear water)	100–33	33–0	0
2. Deposits			
Mode of deposition	Grain-by-grain, dominated by traction processes	Rapid grain-by-grain aggradation from both suspension and traction	*En masse*
Stratification	Massive or horizontal stratification (with cross-stratification)	None or horizontal stratification	None
Grading	Variable: as a result of sequential processes rather than a single process	Frequently distribution normal graded (coarse on bottom, fine on top)	None; reverse; reverse to normal, coarse-tail normal
Sediment characteristics and texture	Clast-supported with an open framework or distinctly finer grained matrix of infiltrated sand; rounded clasts; wide range of particle sizes; sorting from front to tail; *b*max - < 100 mm to > 200 mm	Clast-supported, with predominantly coarse sand, moderate to poorly sorted, *b*max typically < 180 mm	Matrix-supported; rarely clast-supported; very poor to extremely poor sorting; extreme range of particle sizes; *b*max 60–230 mm, may contain megaclasts – 400 mm
Clast long-axis (A) orientation; imbrication	Always perpendicular to flow; usually well imbricated	Large cobble to boulder – usually perpendicular to flow; pebbles to small cobbles – usually parallel to flow; weak imbrication and collapse packing	Variable, based on location within flow; parallel to flow is most prominent; weak to no imbrication
Landforms and deposits	Bars, fans, sheets, splays, channels have large width-to-depth ratio	Similar to water flood	Marginal levees, term. lobes, trapezoidal to U-shaped channel

TABLE 3 *Time classes relevant for forestry*

Time period (years)	Category
0–50	Significant
50–100	Important
100–200	Moderate
200+	Low

TABLE 4 *Power of hydrogeomorphic events based on impact to forest stands*

Power	Forest stand description	Forest stand type
Nil	No effect on forest stands.	FS-1
Low	Original stand remains, although it may have been killed by the event. A younger cohort may be established on the sediments from the event.	FS-2
Moderate	Original stand has been thinned by an event with a younger cohort established on the sediments. Trees from the original stand may be found in debris piles.	FS-3
High	Original stand is removed by an event. A younger cohort is established on the sediments. Trees from the original stand may be found in debris piles.	FS-4

Watershed morphometrics are determined by GIS analysis. The basic attributes include watershed area, relief, basin length, length of stream channels, and area of potentially failing slopes. The attributes were selected due to their influence on the processes influencing fans, namely peak streamflow generation and erosion.

The Melton Index is calculated by dividing relief by the square root of the watershed area (Melton 1965). This index has been found to be reliable for differentiating watersheds with alluvial or debris flow fans (Jackson et al. 1987). Characteristically, watersheds with an index of < 0.25–0.30 have alluvial fans, while debris flow fans are associated with higher indices.

Basin shape (Rf) is determined by dividing watershed area by the square of watershed length. The theory is that equidimensional (round) watersheds (Rf = 0.7854) have a shorter time of concentration and thus high peak flows than elongated watersheds (e.g., Rf = 0.07958) (Strahler 1964). Similarly, drainage density has been associated with peak flows: the higher the density, the higher the peak flows (Patton and Baker 1976). Basin magnitude, the number of first-order streams, is also linked to hydrologic response (Shreve 1966, 1967).

The hypsometric integral is the area under a curve representing the percentage of a watershed below a given elevation (Strahler 1952). A low integral is found in watersheds with most of the area at lower relative elevations. The higher the integral, the more area is found at higher relative elevations. While the integral is related to long-term erosional development of the watershed, it also may be used as an attribute for peak flow generation (e.g., the extent of watershed in the high-elevation snowmelt zone).

Relief ratio is relief divided by basin length. This ratio has the potential to be linked to both runoff and erosion (Schumm 1956).

Terrain stability maps were not available for study watersheds, so area between 30 and 40° was chosen as an approximation of the extent of unstable soils (Jim Schwab, B.C. Ministry of Forests, pers. comm., 2000). The forest cover maps produced by the B.C. Ministry of Forests have a designation for actively failing soils (ESI). This value is being explored; however, it applies only to forested areas of a watershed and may therefore underestimate the total extent of erosion-prone sites. Bedrock geology will be used as a watershed attribute; however, we were not able to access the GIS data for this paper. Our intent is to use a system such as Selby's (1980) to characterize bedrock erodability.

INITIAL RESULTS

Field- and map-based data have been collected on 16 unlogged and 14 logged fans to date. The analysis is currently under way; however, a series of trends is apparent, and preliminary interpretations can be made.

Morphology of Fans

The range of fan morphology in the study area reflects historic and contemporary hydrogeomorphic activity. Low-gradient fans formed by alluvial deposition characteristically have larger watersheds (> 12 km^2). Steeper-gradient fans formed by debris flows have smaller (< 12 km^2) watersheds. Contemporary activity does not always reflect the mode of fan origin.

Evidence of paraglacial fans range from remnants along the main valley sides to major portions of the original deposits. The contemporary fan surfaces are generally 6–10 m below these deposits. Erosion of the original deposits is most likely due to a decline in sediment delivery from the watershed.

Contemporary fan activity ranges from entrenchment to actively growing. Very few fans were found to be in a "steady state equilibrium." Entrenchment is occurring on alluvial and debris flow fans. It appears as though debris flow scour rather than fluvial action is causing the entrenchment on most debris flow fans. Of note, ancient debris flow levees are having a similar effect on the morphology of some fans, as has been reported for entrenched fans. This takes the form of fan elongation, with the transport of coarser sediments further down the fan.

Forest Stands as Indicators of Hydrogeomorphic Activity

Forest stands are a generally reliable information source for the frequency, power, and extent of hydrogeomorphic events. However, there appear to be several limitations. It is generally difficult to take wedges from trees with scars that are older than approximately 50 years (felling is necessary and we have not done this). Growth responses from an event can range from abrupt negative to abrupt positive growth, including no response even on buried trees. A negative growth response (consisting of an abrupt reduction in ring widths) is the result of deep burial and changes in soil water conditions. A positive growth response (an abrupt increase in ring widths) can be related to the removal of competition or an improvement in soil water conditions. Positive growth responses were found on some buried trees. Approximately 30 dendrochronology samples were taken per fan.

All conifer and deciduous species in the study area were observed to develop adventitious roots after burial by sediments. The critical burial depth that causes mortality has not been determined. Buried trees are apparent due to their lack of "butt flare" (Figure 2). The time taken to regain butt flare appears to be at least 50 years.

We are classifying the power of hydrogeomorphic events by the effect on forest stands (Table 4). Four classes are used, ranging from no effect to

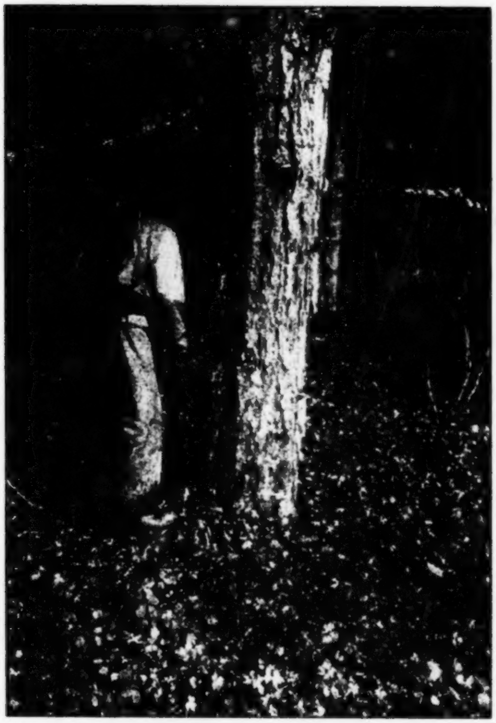

FIGURE 2 *Sediments have buried the butt of this tree. Lack of the characteristic "butt flare" is an indication of active sediment deposition.*

complete removal of the original stand. Of the 30 fans explored, no fans were identified as having FS-1 stands (no effect from hydrogeomorphic events). Only two fans were found with FS-2 stands representing the most powerful events. No fans were described with only FS-3 stands representing the most powerful events. Most fans have FS-4 stands (high power). These fans also have FS-2 and FS-3 stands (low to moderate power) at the margins of the FS-4 stands.

We have observed that the extent of disturbance from hydrogeomorphic events on most fans is limited to swaths of 10–20 m wide, primarily along stream channels that range from 2 to 6 m wide. Such narrow zones of disturbance are very difficult to detect on air photographs, particularly where the forest cover is moderately open due to devil's club (*Oplopanax horridus*) ecosystem associations. The fans with the widest zones of disturbance are alluvial fans (≥ 180 m).

Hydrogeomorphic Role of Forests on Fans

Forests and woody debris influence the transport and storage of sediments, and erosion on a fan surface. It is common to observe lateral and terminal confinement of sediments from hydrogeomorphic events due to stems and large woody debris. In some cases, the volume of stored sediments can be significant (Figure 3). In other cases, the amount stored per event may be small, but incrementally may lead to the development of fine-textured levees and an elevation of the stream channel above the general fan surface. In cases where an avulsion occurs, the stream energy is frequently dissipated across

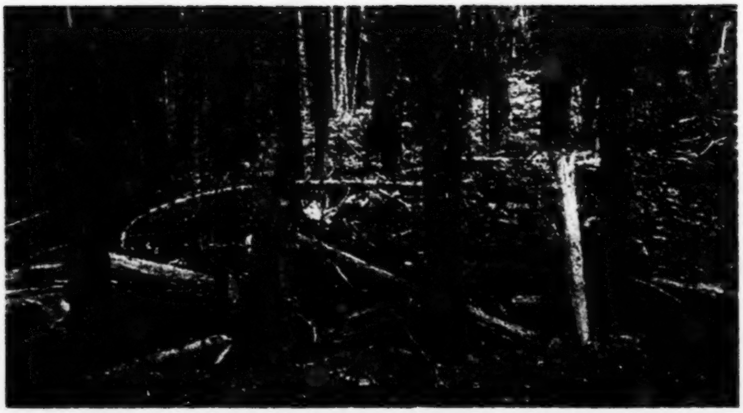

FIGURE 3 *Woody debris held by standing trees can lead to significant sediment storage. In situations like this, it is prudent to prescribe reserves to maintain the hydrogeomorphic role of trees.*

the fan surface by woody "obstructions." In many situations, it appears as though subsequent hydrogeomorphic events lead to the re-establishment of the original stream channel.

The hydrogeomorphic role of forests on our study fans ranges laterally out from the stream channel from zero to several hundred metres. The paths taken by events are usually along old channels, although downed woody debris can play a significant role in redirecting events.

Streams on Fans

Streams are a common feature on fans, and the stream is often at the highest location of the fan cross-section. This appears to be due to levees and the hydrogeomorphic role of forests.

Streams on fans can range from entrenched (by up to 5 m) to unconfined (very low banks). Frequently, channel dimensions are determined by hydrogeomorphic events rather than by fluvial action. Channel substrate can range from fluvial sediments to large colluvial lag sediments. Large woody debris (LWD), both as individual pieces and log jams, can act as hydraulic structures, limiting down-cutting of the channel. LWD can also cause avulsions on several fans. Large woody debris can increase lateral channel erosion; however, this fluvial activity was observed to be generally minor compared with the hydrogeomorphic process influencing the channel. Structures formed by clasts range from none in channels with a history of recent events, to strong in channels that have not experienced disturbance for a long period of time.

Even on debris flow fans, streams on fans are a major source of operational forestry challenges. Generally, the problems arise because drainage structures are sized to allow water flow and are insufficient for bedload and woody debris. Multiple channels on fans also lead to problems because, in any given event, all water and debris may be transported down one rather than all channels. As a result, drainage structures are usually significantly undersized to handle the resulting flows.

Watershed Attributes

Fans are directly influenced by the supply of water, sediment, and woody debris from their watersheds. We are exploring a series of watershed morphometrics and attributes that are related to water and sediments to determine which factors are sensitive to hydrogeomorphic processes. Table 5 presents a subset of our data.

The Melton Index is characteristically greater than 0.25–0.3 in debris flow–dominated watersheds (Jackson et al. 1987). However, in Mill Creek, there is no evidence of contemporary debris flows on the fan, although the index is 0.879. The presence of snow avalanches that are influencing the whole channel within this watershed may have a strong influence on the lack of debris flows.

Roads on Fans

Forest roads are an integral component of forestry activities and represent the highest risk for fan destabilization. We found a series of design, construction, and maintenance issues repeated on destabilized fans (summarized in Table 6).

Inappropriate road locations and drainage structures on fans can be expensive. On one study fan, more than $600 000 was spent to relocate a road and install an adequate bridge. The original road and undersized bridge led to an avulsion, and subsequent attempts to control the stream and add a jump span to the original structure proved unsuccessful. Commonly, eroded roads are abandoned and no attempts at fan restoration are made due to the prohibitive costs and technical challenges. In most cases, inappropriate roads and drainage structures exacerbate impacts from hydrogeomorphic events.

Logging on Fans

Logging on fans involves the removal of tree stems and generally an increase in the amount of small and large woody debris as well as the disruption of downed large woody debris. Ground disturbance can be continuous as a result of skid trails or discontinuous as a result of winter harvesting or cable yarding. The B.C. Forest Practices Code requires riparian reserves on fish-bearing streams or streams that are directly tributary to fish streams. The streams on many fans do not have fish; as a result, riparian reserves are not always left.

The two main logging-related effects on fan stability are due to the removal of forests that play an active hydrogeomorphic role and skid trails that intercept broadcast flows.

DISCUSSION

Forests have been described as "silent witnesses" to hydrogeomorphic processes (Schweingruber 1996). At the stand level, the evidence is in structure, composition, and age-class distribution. At the tree level, the evidence is in scars and abrupt changes in growth. Forests can provide information on the frequency, power, and areal extent of hydrogeomorphic events. For these reasons, forest stands were chosen as the leading indicator for a hazard classification of hydrogeomorphic activity on fans. A key to the utility of trees as a leading indicator is that forestry staff are familiar with trees and readily learn to see the signs.

The original concept in this project was that a whole fan would be hazard-classified based on the highest Forest Stand Type. However, with the sampling to date it is apparent that classifying zones on fans is more appropriate. A major reason for this is the limited extent of disturbance from hydrogeomorphic events on most fans. Significant portions of many fans in our study present no apparent hydrogeomorphic hazards for forestry

TABLE 5 *Some watershed attributes associated with fans that have Forest Stand Types 1, 2, and 4 (abbreviations for biogeoclimatic zones are in the section describing the study area)*

Attribute	Carrigan	Shedin	Mill	Compass	Wan	Legate	Tsez-akwa	Kits
Biogeoclimatic zones (fan/watershed)	ICH/ ESSF	ICH/ ESSF, AT	ICH/ ESSF	ICH/ ESSF, AT	ESSF/ AT	CWH/ MH, AT	SBS/ ESSF, AT	ICH/ ESSF, AT
Forest Stand Type on fan	FS-2	FS-2	FS-2	FS-4	FS-4	FS-4	FS-4	FS-4
Hydrogeomorphic process	Hyper. flow	Debris flow to apex	Flood	Hyper. flow	Debris flow	Debris flow	Flood	Debris flow
Frequency class (years)	100	0–50	0–50	0–50	0–50	0–50	50–100	0–50
W/S area (km^2)	1.560	4.824	1.408	18.220	1.286	1.318	99.266	0.493
Melton Ruggedness Index	0.382	0.464	0.879	0.345	0.655	1.076	0.159	0.785
Hypsometric integral	0.654	0.497	0.542	0.424	0.504	0.520	0.372	0.539
W/S shape	0.557	0.165	0.302	0.294	0.361	0.221	0.291	0.387
Relief ratio	0.285	0.188	0.483	0.187	0.394	0.505	0.086	0.488
Drainage density km/km^2	2.517	2.573	2.613	2.654	2.325	4.019	1.795	6.170
% W/S 30–40°	14.3	0.9	59.5	21.2	31.6	39.6	4.2	40.9
% W/S ESA1	0	0	53	14	3	29	4	30
Snow avalanche	Nil	Nil	Whole channel	Valley sides	Whole channel	Whole channel	Valley sides	Valley sides

TABLE 6 *Some common road problems and solutions*

Some common road problems	Solutions
Roads climb to stream crossings	Roads drop to stream crossings/cross at apex
Roads built at slope break in stream/fan	Cross streams in uniform slope reaches
Ditches	No ditch lines/limit road width
Lack of cross-drainage	Use rolling grade in old channels/frequent cross-drains
Drainage structures affect channel hydraulics	Structures with rectangular cross-section
Excavation into stream channel–channel destabilization	Place rip-rap to maintain channel stability if excavation is required
Inadequate drainage structures–multiple channel situations	Design all structures in multiple channel situations to handle all the flow or to be "fail safe"
Roads not deactivated	Deactivate roads and structures ASAP/build with deactivation in mind
Breached streambanks	Do not breach banks/reconstruct with deactivation
Skid trails on fans channel water	Limit skid trails, deactivate and replace LWD

activities. Given the limited areal disturbance even on fans experiencing powerful events, air photo identification of disturbances can be difficult to impossible. Fieldwork is required to identify the nature and extent of hydrogeomorphic disturbances on most fans.

Our observations indicate that forests can play an important hydrogeomorphic role on fans. Irasawa et al. (1991) found that forested fans subject to debris flows had steeper slope gradients due to the storage of sediments on the upper fan surface. This storage role appears to be occurring with a tendency for the stream channel to remain in its original location. Trees and woody debris act as major roughness elements during the early stages of an avulsion. In general, a stream has difficulty in establishing a new single-thread channel. As a result, deposition occurs on the forested fan surface and it is common for the stream to return to its original channel (Sato 1991). In addition, large woody debris and debris jams in the stream channel act as hydraulic structures, storing sediments and limiting channel down-cutting (Keller and Swanson 1979). As a consequence, the cross-sections of fans characteristically have the stream channel at the highest location. However, once a "successful" avulsion occurs, it is unlikely that the stream will return to its original location. This situation was observed on several logged or roaded fans, particularly where no, or narrow, riparian reserves were retained.

The B.C. Forest Practices Code specifies widths of riparian zones for streams that have fish or streams that are directly tributary to fish streams. The reserve widths are primarily based on the average height of trees adjacent to streams (e.g., 30 m). Our observations indicate that both the rationale for reserves and their widths should be revisited, given the important hydrogeomorphic role played by forests on many fans.

First, many fans have streams that do not have fish and thus there is no legislated requirement for reserves. We have consistently observed that the removal of hydrogeomorphically active forests has dramatic effects on streams and fan surfaces. In particular, we noted channel avulsions, channel entrenchment, channel widening, dewatering, and sediment deposition across fan surfaces. The nature and extent of these disturbances are considerably greater than would be expected in a forested situation. The resulting impacts are to forest growing sites, roads, stream ecology, and aesthetics.

Second, basing reserve width on average tree height is not appropriate because the zone of hydrogeomorphically active forests on fans is not a function of tree height. Rather, the zone is determined by the trajectories of hydrogeomorphic events, topographic differences that are sometimes subtle, and stochastically through the presence of large woody debris. It is appropriate to combine these features with dendrochronology and stand information to tailor reserves and management zones for individual fans.

A management zone is generally specified next to a riparian reserve. Given that future hydrogeomorphic events may extend further than contemporary evidence suggests, it is prudent to leave high stumps and large woody debris in the management zone to act as future sediment traps. Of note, we inspected stumps on a fan with a reserve and found evidence of recent and historic debris flow scars (dating back over 400 years). In this case, more attention should have been paid to the reserve layout. In addition, there was no management zone to protect the reserve from windthrow that was already occurring 2 years post-harvesting.

Logging activities on a fan can influence fan stability. In particular, we observed that skid trails can intercept and concentrate overland flows. The trails become new stream channels and experience considerable erosion as a result unless there are rolling dips, cross-ditches, or woody debris placement.

When dealing with fans there is perhaps a tendency to focus on dramatic erosional events such as major floods or debris flows that occur irregularly. However, streams on fans pose a hazard for forestry activities due to annual or biannual high flow periods (spring snowmelt and fall rain or rain-on-snow). Bedload and debris movement can challenge drainage structures seasonally, and if undersized or not adequately maintained, can lead to significant erosion of roads. In addition, we observed that where channel excavations for drainage structures are not buttressed with rip-rap, sediments from channel erosion can quickly overwhelm drainage structures.

Fans are a product of, and influenced by, the water and sediment being delivered from their watershed. For this reason, we are exploring the significance of watershed morphometrics and features. At this point, the analysis is still under way; however, we have made several initial conclusions. It appears as though snow avalanches may condition a stream channel such that the dominant sediment transport mechanism is bedload movement rather than debris flows. Characteristically, snow avalanche channels have limited riparian forests and very few accumulations of woody debris. As a result, sediment storage tends to be continuous along a channel rather than in discrete accumulations that are prone to debris flow mobilization. It also appears that most of the study fans are of paraglacial origin, and that contemporary hydrogeomorphic activity on some fans has shifted from debris flows to hyperconcentrated flows and floods. Thus, floods may be the contemporary hydrogeomorphic process on a fan with a gradient of $> 4°$ and a watershed with a Melton Index > 0.25.

One sage forester has commented that from a roads perspective, fans can be classed into three categories: no problem, nuisance, and problem (D. Keating, pers. comm., 2000). We found very few roads on fans that were "no problem." Most roads on fans have cost a considerable amount of money to maintain in a safe condition. Most of the problems we observed can be avoided or addressed in road design, construction techniques, maintenance, and deactivation (Table 6). However, it is crucial to identify fan landforms early in the planning process. This is generally not happening and, as a result, many situations develop into expensive "nuisances and problems."

Information about the frequency, power, and extent of impact from hydrogeomorphic events is central to developing appropriate forestry prescriptions. However, this information provides only part of the hazard assessment. Previous events or processes may have set the stage for imminent future challenges on a fan. For example, bedload aggradation may predispose a stream to an avulsion. Identifying these situations is necessary, given the long-term implications of many forestry activities.

CONCLUSIONS

Identifying hydrogeomorphic hazards for forestry on fans is central to sustainable forest management. However, even "safe" fans can be destabilized with inappropriate prescriptions for riparian zones, stream crossings, road locations, cross-drainage, and deactivation. Using the analogy of unstable slopes, all fans should be considered as class IV terrain unless proven otherwise. Special attention must be paid to all forestry activities.

As with terrain stability recognition, most operational forestry staff require office and field training in the recognition of fans and the signs of hydrogeomorphic activity. Until the landforms and hazards are identified operationally, forestry activities on fans will continue to be problematic.

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LITERATURE CITED

Baker, V.R., R.C. Kochel, and P.C. Patton (editors). Flood geomorphology. John Wiley, New York, N.Y.

Banner, A., W. MacKenzie, S. Haeussler, S. Thomson, J. Pojar, and R. Trowbridge. 1993. A field guide to site identification and interpretation for the Prince Rupert Forest Region. B.C. Min. For., Smithers, B.C. Land Manage. Handb. 26.

Beaty, C.B. 1970. Age and estimated rate of accumulation of an alluvial fan. White Mountains, California. Am. J. Sci. 268:50–77.

British Columbia Ministry of Forests. 1999. Mapping and assessing terrain stability. 2nd ed. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

Bull, W.B. 1977. The alluvial-fan environment. Prog. Phys. Geogr. 1:222–70.

Coates, K.D., S. Haeussler, S. Lindeburgh, R. Pojar, and R.J. Stock. 1994. Ecology and silviculture of interior spruce in British Columbia. B.C. Min. For. and Can. For. Serv., Victoria, B.C. FRDA Rep. 220.

Costa, J.E. 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. *In* Flood geomorphology. V.R Baker, R.C. Kochel, and P.C. Patton (editors). John Wiley, New York, N.Y. pp. 113–22.

Costa, J.E. and G.F. Wieczorek (editors). 1987. Debris flows/avalanches: process, recognition, and mitigation. Rev. Eng. Geol. Vol. VII. Geol. Soc. Am., Boulder, Colo.

Denny, C.S. 1965. Alluvial fans in the Death Valley region, California and Nevada. U.S. Geol. Survey Prof. Pap. 466.

———. 1967. Fans and pediments. Am. J. Sci. 265:81–105.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. B.C. Dep. Mines and Petroleum Resour., Victoria, B.C. Bull. No. 48.

Hooke, R.L. 1968. Steady-state relationships on arid-region alluvial fans. J. Geol. 75:438–60.

Howes, D.E and E. Kenk. 1988. Terrain classification system for British Columbia. B.C. Min. Environ., Lands and Parks, Victoria, B.C. MOE Man. 10.

Hunt, C.B. and D.R. Mabey. 1966. Stratigraphy and structure. Death Valley, California. U.S. Geol. Surv. Prof. Pap. 494-A.

Irasawa, M., Y. Ishikawa, A. Fukumoto, and T. Mizuyama. 1991. Control of debris flows by forested zones. *In* Proc. Japan-U.S. Workshop on Snow Avalanche, Landslide, Debris Flow Prediction and Control. Sept. 30–Oct. 2, 1991, Tsukuba, Japan. Science and Tech. Agency of Japanese Gov. pp. 543–50.

Jackson, L.E., R.A. Kostaschuk, and G.M. MacDonald. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. *In* Debris flows/avalanches: Process, recognition, and mitigation. J.E. Costa and G.F. Wieczorek (editors). Rev. Eng. Geol. Vol. VII. Geol. Soc. Am., pp. 115–24.

Keller, E.A. and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361–80.

Melton, M.A. 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. J. Geol. 73:1–38.

Oliver, C.D. and B.C. Larson. 1996. Forest stand dynamics. John Wiley, New York, N.Y.

Patton, P.C. and V.R. Baker. 1976. Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Water Resour. Res. 12:941–52.

Pierson, T.C. and J.E. Costa. 1987. A rheologic classification of subaerial sediment-water flows. *In* Debris flows/avalanches: Process, recognition, and mitigation. J.E. Costa and G.F. Wieczorek (editors). Geol. Soc. Am. Rev. Eng. Geol. Vol. VII, pp. 1–12.

Ritter, J. and 16 others. 1993. Quaternary evolution of Cedar Creek alluvial fan, Montana. Geomorphology 8:287–304.

Ritter, D.F., R.C. Kochel, and J.R. Miller. 1995. Process geomorphology. 3rd ed. Wm. C. Brown Publishers. Dubuque, Iowa.

Ryder, J.M. 1971a. The stratigraphy and morphology of paraglacial alluvial fans in south-central British Columbia. Can. J. Earth Sci. 8:279–98.

———. 1971b. Some aspects of the morphometry of paraglacial alluvial fans in south-central British Columbia. Can. J. Earth Sci. 8:1252–64.

Sato, T. 1991. Flood disaster with drifted logs and sand in Aso Volcano. *In* Proc. Japan-U.S. Workshop on Snow Avalanche, Landslide, Debris Flow Prediction and Control. Sept. 30–Oct. 2, 1991. Tsukuba, Japan. Science and Tech. Agency of Japanese Gov., pp. 497–506.

Schumm, S.A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol. Soc. Am. Bull. 67:597–646.

Schweingruber, F.H. 1996. Tree rings and environment dendroecology. Paul Haupt Publishers. Berne, Switzerland.

Selby, M.J. 1980. A rock mass strength classification for geomorphic purposes: with tests from Antarctic and New Zealand. Zeit. f. Geomorph. 24:31-51.

Septer, D. and J.W. Schwab. 1995. Rainstorm and flood damage: northwest British Columbia 1891–1991. B.C. Min. For., Victoria, B.C. Land Manage. Handb. 31.

Shreve, R.L. 1966. Statistical law of stream numbers. J. Geol. 74:17–37.

———. 1967. Infinite topographically random channel networks. J. Geol. 75: 178–86.

Smith, G.A. 1986. Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process. Geol. Soc. Am. Bull. 97:1–10.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Amer. Bull. 63:1117–42.

———. 1964. Quantitative geomorphology of drainage basins and channel networks. *In* Handbook of hydrology. V.T. Chow (editor). McGraw-Hill, New York, N.Y. pp. 439–76.

VanDine, D.F. 1985. Debris flows and debris torrents in the southern Canadian Cordillera. Can. Geotech. J. 22:44–68.

Wells, S.G. and A.M. Harvey. 1987. Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England. Geol. Soc. Am. Bull. 98:182–98.

Mapping and hazard assessment of large deep-seated landslides in forested landscapes

TERRY ROLLERSON, JUNE RYDER, JOHN COYLE, AND ZHONGYOU LU

Definitions and criteria for the landslide hazard ratings currently used in terrain stability mapping for forestry in British Columbia are strongly oriented toward shallow translational landslides, primarily the likelihood of initiation of debris slides and associated debris flows. However, deep-seated landslides, ranging from earthflows to slow slides in bedrock, are common in many parts of the province. We know that these can be accelerated or reactivated as a result of natural disturbances, such as climate change, seismic events and stream undercutting. Similar changes may result from forestry activities, but little is known about the potential effects of forest roads and/or various silvicultural practices. To date, deep-seated landslides have been rated by ad hoc adaptations of the existing terrain stability classification systems. Difficulties arising include mapping the extent of these features, classification of deep-seated landslides, assessment of current activity, and assignment of hazard ratings.

We discuss these difficulties, propose standard terminology for describing landslide activity, define logical hazard interpretations, and present simple criteria and rationale for hazard ratings. We also suggest modifications to the symbology used in the British Columbia Terrain Classification System to facilitate the description and classification of deep-seated landslides.

Terrain attribute studies, Vancouver Forest Region

TOM MILLARD AND TERRY ROLLERSON

Terrain attribute studies (TASS) examine previously logged and roaded terrain so that predictions can be made as to the likely locations of future forestry-related landslides. We examine the results of six TASS in the Vancouver Forest Region (VFR). Comparisons between these studies show interesting trends and contrasts. Average clearcut landslide rates vary by an order of magnitude within the VFR. Similarly, there is an order of magnitude range in the average roadfill landslide rate in the studies. However, the study location with the highest clearcut landslide rates does not coincide with the location of the highest road landslide rates. Although landslide rates vary across the VFR, there are consistent terrain characteristics that indicate higher or lower landslide hazard. This paper presents landslide rates determined by a single variable: the presence of gullies. Single gullies consistently have the highest or second highest landslide rates of any slope morphology. However, although single gullies are always some of the highest-hazard areas in each study area, landslide rates for single gully terrain still vary by at least an order of magnitude across the VFR. We speculate on the reasons why landslide rates vary across the VFR.

Flowslides and drowned, buried forests at Halden Creek, northeastern British Columbia

MARTEN GEERTSEMA AND JOHN CLAGUE

Halden Creek has been frequently impounded by flowslides. The landslides are recorded in sedimentary exposures in two ways. 1) Trees died in the resultant temporary lakes and were subsequently partially buried by alluvium. The buried portions of the trees were preserved. Bank erosion exhumed these ancient drowned forests. 2) In some cases, multiple organic layers in eroded slide debris record separate flowslide events. Using radiocarbon dates of trees and organic layers, we attempt to reconstruct flowslide history at Halden Creek.

Terrain attribute studies in the Prince George Forest Region, British Columbia

BRENT WARD, TERRY ROLLERSON, AND SID TSANG

A program of terrain stability mapping suitable for forest development purposes has been carried out in coastal British Columbia for over 20 years; however, common use in the Interior regions is limited to post-1995, since the advent of the Forest Practices Code. Terrain stability mapping assesses the likelihood of post-harvesting landslides using air photo interpretation and ground checking, usually at 1:20 000 scale. Each terrain polygon is then assigned a slope stability classification based on surficial material, texture, slope gradient, slope morphology, moisture conditions, and ongoing geomorphic processes, such as evidence of previous instability. Due to regional variations in climate, geology, soils, and other factors, few specific criteria can be applied universally across all regions of the province. Thus, this mapping is relatively subjective, being highly dependent on the experience and local knowledge of the mapper. Criteria developed on the Coast are commonly imported to the Interior, resulting in inconsistent, unreliable, or overly conservative mapping.

Terrain attribute studies attempt to empirically quantify which terrain units are most likely to fail following logging and road construction. This allows calibration of slope stability classifications used for terrain stability mapping and should result in more reliable mapping in the Interior. A preliminary terrain attribute study was carried out in the Prince George and Robson Valley Forest Districts in the Prince George Forest Region. The methodology for terrain attribute studies will be described and results presented. Both percentage of failed polygons and landslides per hectare data were calculated.

In the McGregor Watershed, the 56 landslides identified were concentrated in only 21 polygons, out of 268 visited (~8%). This corresponds to 0.007 landslides/ha.

Approximately 70% of the polygons that failed were silty sand glaciolacustrine sediments. The fact that glaciolacustrine terrain makes up only 30% of mapped polygons indicates that this is a problematic terrain type. In the Dore Watershed, the 43 landslides identified occurred in 21 polygons out of 481 visited (~4%). This corresponds to 0.004 landslides/ha. Of the 21 polygons that failed, 20 were in till, reflecting the dominant surficial material in the area. The overall frequency of the two watersheds is 0.006 landslides/ha. This is considerably lower than published results from coastal British Columbia: 0.17 landslides/ha for the Queen Charlotte Islands; 0.08 landslides/ha for Vancouver Island; and 0.01–0.04 landslides/ha for the Coast Mountains.

Chi-Square Automatic Interaction Detection (CHAID) was carried out on the combined data set for clearcut landslides for both percentage of failing polygons and landslides/ha. Based on percentage of failing polygons, CHAID indicated slope group followed by terrain category as the most important variables. Slopes ≥ 31° and especially ≥ 36° and terrain types consisting of glaciolacustrine, glaciofluvial, and till were more likely to fail. Based on landslides/ha, CHAID indicated that terrain category followed by gully wall slope angle as the most important variables. Terrain types consisting of glaciolacustrine and glaciofluvial with gully wall slope angles ≥ 34° were more likely to fail. Implications of these results for terrain mapping will be discussed.

The use of SINMAP in terrain stability mapping in the Prince George region—two case studies

ROBERT PACK, DENNY MAYNARD, AND MARTEN GEERTSEMA

Terrain stability mapping for B.C. Forest Practices Code requirements follows standardized guidelines (Resource Inventory Committee [RIC] standards). Classifications resulting from these guidelines are largely based on geomorphic interpretation derived from field observation, air photo interpretation, and the assessment of regional stability criteria. Standard products include a terrain classification (base data) map, and an interpretive map that highlights terrain stability classes. A new methodology has been developed that promised to complement these conventional interpretations. SINMAP (Stability INdex MAPping) is an ArcView GIS extension that facilitates the assessment of terrain stability at the watershed scale. SINMAP has as its theoretical basis a probabilistic formulation of the infinite plane slope stability model. Digital elevation model (DEM) data are used to estimate the slope of the terrain as well as the potential soil moisture conditions as influenced by topographic flow convergence. Other parameters considered in the model include soil friction and transmissivity, root cohesion, and water recharge. Parameters can be adjusted so that the resulting stability map maximizes the "capture" of observed landslides in regions with a low stability index, while minimizing the extent of low-stability regions and consequent alienation of terrain to regions where landslides have not been observed. The utility of this method in augmenting or assisting terrain stability mapping is discussed in the context of two study areas in the Prince George Forest Region. The subject areas include Foster Creek and Canoe Mountain in the Robson Valley Forest District.

Terrain stability mapping—practice guidelines

IRENE WEILAND, DENNY MAYNARD, AND TIM GILES

The taskforce on professional practice in terrain stability mapping was formed under the auspices of the Division of Engineers and Geoscientists in the Forestry Sector (DEGIFS) as a result of discussions during the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) conference in Whistler, B.C. in October 2000. The taskforce consisted of consultants, Ministry of Forests staff, and forest industry personnel experienced in terrain stability mapping. The taskforce objectives were to develop practice guidelines specific to terrain stability mapping (TSM) under the Forest Practices Code (FPC). The intended audience are practitioners (mappers), quality assurance reviewers, and forestry managers who administer TSM projects. The practice guidelines are intended to build on the existing FPC and Resource Inventory Committee (RIC) publications that set the current standards for TSM; and to clarify or more thoroughly explain procedures that are inadequately covered in the existing publications. The taskforce is currently producing a first draft.

Specifically, the taskforce has discussed the following topics: reliability and limitations of TSM; mapper qualifications and experience; standards for detailed and reconnaissance TSM; issues around map-upgrading; contract and proposal specifications; and publication of a user guide directed towards land managers, operational staff, and professionals in related disciplines.

How "risky" are old roads?

MIKE MURRELL

Road deactivation in the past has been based on the "whole watershed" approach. While this ensured that all roads were stabilized within a priority watershed, it did not address the possibility that a "high-risk" road could be present and disregarded in a non-priority watershed.

A "risk assessment" method has been developed in Squamish, B.C. to rapidly and economically identify and quantify the associated environmental risk of roads by examining them for visual signs of deterioration and considering the probable consequences to:

- people (human factor);
- the fish (in-stream factor); and
- the forest (upslope factor).

By identifying and quantifying both the hazard and the probable consequences, a simple calculation can result in a numerical risk and a subsequent ranking of all identified trouble spots. Although this reconnaissance method is limited to roads that are not completely overgrown or canopied, it quickly allows the screening of extensive road systems to help establish priority areas regardless of the tenure situation.

The method involves flying slowly over roads to recognize signs of instability, then judging when an "event" could occur (i.e., the hazard), followed by a judgement of what the damage would likely be to each of the three "factors" (i.e., the consequence). The hazards and consequences are quantified by using a chart of increasing magnitude. Five numbers are entered into a spreadsheet that computes, rationalizes, and combines the resultant risks and produces a mini-graph for each identified road section. The graphs are then pasted onto a 1:50 000 base map for display purposes.

"Decision makers" can use the spreadsheets and maps as a tool to assist them in planning and justifying road deactivation projects. Contrarily, it helps them decide if a road section's risk is too low to warrant work—that is, it has "acceptable risk."

Risk management is nothing more than examining the "risk assessment" results and deciding what to do about them. For road deactivation, this can vary from "do nothing" to "full deactivation and rehabilitation." Risk can be reduced to an acceptable level by altering one or more of the following:

- the source
- the path, and/or
- the receptor,

and can be explained by the "tipping rock" scenario.

This presentation will present the rationale leading to the present method, will explain the method itself, will present some of the results from the 1999 fieldwork in the Squamish Forest District, and will display some of the maps generated.

Landslide susceptibility from watershed and fan characteristics, Salmon Arm and Vernon Forest Districts

AXEL EICHEL AND TED FULLER

Landslide occurrence in the Salmon Arm and Vernon Forest Districts in the last 5 years has stimulated research to determine how small drainage basins might be classified into debris flow-prone, debris flood-prone, or flood-prone. Alluvial fans situated at the base of several entrenched stream systems may have people dwelling on them. In addition to safety concerns, water quality and habitat are also of importance. A procedure is presented here that uses both map-based (GIS) and field-based (fan and channel mapping) analysis to show relative risk of impact on fans. Bedrock and surficial geology are used to type the basins that are dominated by metamorphic rocks. Basin area, aspect, slope, inner gorge, and gentle-over-steep conditions were determined. GIS-generated channel longitudinal profiles were compared between the data sets. Fan morphology and stratigraphy aided in identifying previous debris flow events and their magnitude. Historical information provided by time-series air photo interpretation, historic maps, and archival research provides clues to recurrence intervals. Some fans will have relict paraglacial deposits that include debris flows and may still support future debris flows. The methods proposed here can be used to signal special concerns for forest development. The use of this template may find application in risk assessment outside the selected forest districts.

An application of risk analyses in the forest sector using judgemental probability and decision (fault) tree analysis

DOUG NICOL

Judgemental probabilities and fault tree analyses have been used to estimate the risk associated with specific forest road segments to downslope resources. An example is reviewed showing its application.

The example arises as a result of 1960's and early 1970's logging practices. Two small creeks located in the northern portion of the Arrow Forest District in southeastern British Columbia contained debris from the construction of old trails and roads. Some of this debris/fill is now failing as a result of diverted water and rotting organics. One of the creek channels is within a domestic watershed while the other is located above a residence. Adjacent gullies have experienced road-related fill slope failures as a result of the old skid trails/roads. The identified hazards entailed debris slides and debris flows that would potentially mobilize to the valley bottom. A traditional forest sector risk analysis would consist of identifying the hazard qualitatively (hazard simply consisting of likelihood of landslide) multiplied by a qualitative consequence (low, moderate, or high).

For comparison purposes, the risk was estimated using a decision tree (fault tree) analysis through the application of judgemental probabilities. The decision tree analyses provided additional clarity with respect to the level of risk and allowed the resource managers to better evaluate the risk and determine the level of required remedial works.

Potential consequences of logging and road building upslope of unstable terrain: Planning implications

DAVID TOEWS

Logging and road building above potentially unstable terrain can increase the probability of landslides. There are several guidelines that address this situation. In the Forest Practices Code (FPC) Guidebook for community watersheds there is a guideline that limits the extent of logging above potentially unstable terrain to 20% of the drainage area. Also, in the Kootenay-Boundary Land Use Plan there is a similar guideline that applies to all areas in the Nelson Forest Region in southeastern British Columbia. Professional hydrologists and geoscientists are frequently asked to investigate individual situations to determine if this guideline can be safely exceeded. This presentation will discuss a number of field situations that have been investigated in the Kootenays. The roads associated with development pose a greater risk than the logging itself. The strategy should be to maintain natural drainage patterns. Logging also poses an incremental risk, although a smaller one, and should also be limited in these situations. In order to produce a credible analysis of the risks and options available, the professional geoscientist or hydrologist must work closely with the development forester.

Promoting better management through stumpage incentives

JIM SMITH

Road density and, to a lesser extent, Equivalent Clearcut Area (ECA), are directly associated with the risk of landslides and sediment production. This is particularly important when operating in consumptive watersheds and areas with high-value fisheries. As the forest industry begins to move into these contentious areas, incentives to reduce risk factors should be developed. The stumpage appraisal system is designed to assess costs associated with the average efficient operator in most conventional forest industrial development. The system presently promotes road building and is commonly used as a mechanism to reduce stumpage rates on cutting permits. Access alternatives that have less impact, such as long skidding or forwarding, are discouraged by the system. As well, cost allowances for silvicultural systems, which minimize ECA, should be encouraged. The appraisal system is a powerful tool that should be used by government to promote development options that reduce risks to water resources in these valuable watersheds.

Managing the Coldstream Creek landslide: An example of applying incremental landslide stabilization techniques

KEVIN TURNER, JOHN DONNELLY, AND DRUM CAVERS

The Coldstream Creek valley is a community watershed located just east of Vernon, B.C. Besides supplying water for the Coldstream Irrigation District, the watershed is managed for forestry and range operations, and, being proximate to a major population centre and to Silver Star Provincial Park, it has an intensive level of public and recreational use. In the spring of 1996, a

3.6-ha slump initiated in a narrow canyon at the outlet of the valley, effectively cutting off access into the watershed. The landslide occurred following an extended period of above-normal annual precipitation. The high rate of slump movement (i.e., some 30–40 mm per day) precluded the typical "fix and forget" management technique. The steep terrain and private property that exists around the landslide made bypassing the slump a risky, difficult, and expensive option. Accordingly, attempts to stabilize the slide using a variety of techniques were undertaken between 1996 and 1999. These techniques involved survey monitoring, slope buttressing, site drainage alteration, trench drain installation, bank stabilization, subgrade ballasting, and horizontal drain installation. The project underscores the value of approaching landslide stabilization projects using a planned geotechnical investigation process, open communication and cooperation amongst the watershed stakeholders, and a program to monitor the results.

Mass wasting events associated with a large-magnitude rain-on-snow event, November 1999, Columbia and Rocky Mountains, southeastern British Columbia

JOE ALCOCK

In November 1999, a large-magnitude rain-on-snow event occurred in the Kootenay Region of British Columbia. In the Columbia Forest District, tens of debris flow, water erosion, and other mass wasting events occurred. Many of the in-block debris flows, water events on pre-and post-Code roads, and natural events were investigated and site-specific causes determined. Generally, the mass wasting and water erosion events generated by the rain-on-snow were different than typical spring snowmelt-caused events. Surface and subsurface drainage volumes were often beyond ditch and culvert flow capacity. Surface water flow occurred in new, untested locations. Debris flows occurred in the uphill portions of cutblocks and in reactivated gully wall failures. Ice and slush avalanches were observed in alpine areas. This major precipitation event served to pinpoint the locations of inadequate drainage structures and unstable sidecast and road gully fills. The adequacy of drainage structures in new and disused forestry roads is evaluated. The effects of snowpack distribution, cutblock boundaries in relationship to terrain stability polygons, and other factors are discussed.

Causes of gentle-over-steep landslides in Arrow Forest District

PETER JORDAN AND DOUG NICOL

In the southern Interior of British Columbia, many landslides related to forest development occur on steep slopes below roads and cutblocks that are on relatively gentle terrain. An important problem in planning forest development is that Forest Practices Code requirements for terrain stability assessments and road design are based on conditions at the site, not on the often more hazardous slopes below.

We have investigated a number of landslide incidents throughout the Nelson Forest Region, including many below cutblocks and roads. Some of these have occurred below "post-Code" roads (those built since the introduction of the Forest Practices Code in 1995). This presentation will focus on several landslides in the Arrow Forest District that illustrate the hydrological and geotechnical processes involved in landslide initiation, as well as the forest planning implications. Two main mechanisms will be discussed: drainage concentration and diversion by roads, and enhanced snowmelt due to clearcuts above potentially unstable slopes.

Coffee Creek landslides and flood event of November 1999

NICHOLE BOULTBEE, DOUG NICOL, PETER JORDAN, AND DWAIN BOYER

On November 11 and 12, 1999, an unusual rainstorm caused flooding and landslides in several areas of the Kootenay region of British Columbia. The area most affected was the Coffee Creek drainage near Balfour, on Kootenay Lake, where serious damage occurred to Highway 31. Several landslides occurred in the watershed, and the Forest Service road along the creek was washed out at many locations.

The relative importance of natural processes, and of landslides and erosion caused by forest development, is an issue that is always raised whenever a damaging hydrologic event occurs. In Coffee Creek, a large landslide in an old cutblock was caused by the rainstorm, and a large natural debris flow occurred in an undeveloped area nearby. Both events added large quantities of sediment to the creek channel, and, downstream from these slides, the channel experienced severe bank erosion and aggradation.

Severe fall rainstorms are very unusual in the Kootenays, where almost all peak flows, as well as landslide and erosion events, occur during spring snowmelt. Information on the climatic and hydrologic causes of the event, and the natural and forestry-related landslides, will be presented.

Recent large-magnitude landslides, Prince Rupert Forest Region

JAMES SCHWAB

Large-magnitude landslides occur on an infrequent basis within the interior portion of the Prince Rupert Forest Region, British Columbia. Where these large landslides occur they have considerable impact to forest land. Four recent large landslides were investigated:

1. Windfall main landslide (Mezidian Lake) was caused by the diversion of creek 300 m down a logging road (7000 m^3 / 20 hr period). Water flowed into a bedrock fault in sedimentary rock. The failure initiated as a bedrock slide of 100 000 m^3 that triggered a debris avalanche, which travelled 900 m to the valley flat. It carried boulders the size of pickup trucks. Total volume transported is in the order of 160 000 m^3. Land area covers 14 ha.
2. Rock avalanche Howson Range (Telkwa pass) originated as a rock topple failure (1×10^6 m^3) from a rock ridge. The rock fell about 150 m onto glacial ice, expanded to cover the ice valley glacier, to a width of 300–400 m, continued down the ice valley, and avalanched into the Limonite Creek valley. The rock avalanche travelled a total distance of 2.6 km, dropping 1300 m in elevation, and severed the Pacific Natural Gas pipeline. The avalanche path through mature forest covered an area 1200 m long by 400 m wide. This area was scheduled for harvest through the Small Business Forest Enterprise Program (SBFEP). Historical rock avalanches have occurred in the Limonite Creek valley. The level of acceptable risk must be considered for forestry operations in potential rock avalanche zones.
3. A retrogressive slide-flow occurred on relatively gentle, completely forested, seemingly benign terrain proposed for timber harvesting (Goat Mountain, Harold Price watershed east of Smithers). Failure was within a deep compact basal till. The landform was dissected by a few minor ephemeral stream channels. There was no evidence of previous large landslides. The landslide covers an area of 6.1 ha. Volume is in the order of 250 000 m^3. The headscarp of the failure bowl is 24–28 m deep. Sliding occurred along an assumed failure plane of 24%. Morphological features resemble failures in sensitive clays. The till is similar to glacial tills found throughout the Bulkley Valley (Liquid Limit 33.5, Plastic Limit 12.1, Plasticity Index 21.4, sand 41.8%, silt 31.0%, clay 27.2%, and bulk density 1.85). The gentle slope and the lack of discernible field indicators suggest that a failure at this site may not have been anticipated through a routine terrain stability field assessment.
4. A large underwater landslide (3×10^6 m^3) occurred off the steep slope of a fan-delta on Troitsa Lake. The visible portion of the landslide measures 400 m by 60 m. A displacement wave 1.5 m high hit the opposite side of the lake 1 km away. A backwash wave 2 m in height crashed back over the head scarp. The north end of the lake (10 km from the landslide), experienced an initial sharp swell about 60 cm in height; bays and shallows were then sucked empty. A large return wave 2 m high crashed through a shallow bay, tearing sunken logs and debris from the bay floor and hurling the debris onto the beach and into the forest surrounding the bay. Boats and floating wharves were ripped from their moorings. The instability of fans and fan-deltas in freshwater fjord-type lakes is mentioned briefly in published literature. However, little documentation exists of known sites and landslide-tsunami events in British Columbia.

Dendrochronology of debris flows on the British Columbia north coast

JAMES SCHWAB

In selected study areas on the British Columbia north coast, debris flows were identified on air photographs and mapped. The identification of failures was repeated for available photo coverage to determine the year of photography when the failure first appeared. A field-sampling program was then undertaken on Graham Island (Queen Charlotte Islands) and in the Prince Rupert area. Failures greater than 1.0 ha in area or large enough to extend into the valley bottom were sampled to determine the possible date of the event. Tree sampling for tree ring analysis was done on slide deposits in the depositional zone or on levees within torrent channels. Generally, 10–15 core samples were obtained for each slide. Scarred trees and trees showing vigorous or suppressed growth that were located along the edge of a slide were also cored or a cross-section disk taken to look for slowing of or release in growth. A search for events recorded in newspapers, journals, technical reports, ship logs, diaries, and company documents was also undertaken to find records and written accounts of storms and landslides. The ages of trees sampled on landslides were then compared and linked to known events. Most of the landslide volume transported occurred during major storm events. Data collected for Graham Island and the Prince Rupert area indicate that six storms over the last 150 years transported 76% of the landslide volume: 9.5%, 14%, 30.9%, 6.5%, 6.4%, and 9.1%, respectively, for the years 1875, 1891, 1917, 1935, 1957, and 1978. This documentation of landslide ages suggests that forest management activity on the north coast has yet to experience the "big storm" similar to the 1917 event.

A handbook for management of snow-avalanche–prone forest terrain

PETER WEIR, PETER JORDAN, AND STEVE CHATWIN

In mountainous regions of British Columbia, forest harvesting is moving onto steeper, potentially avalanche-prone terrain. The B.C. Ministry of Forests has produced a Land Management Handbook aimed at foresters, forest technicians, engineers, engineering technicians, geoscientists, harvest supervisors, and others responsible for managing forests in avalanche-prone terrain. It assists in identifying avalanche-prone terrain and offers principles useful for planning silvicultural operations, cutblock configuration, and harvesting systems to minimize resource losses to snow avalanches.

The handbook highlights:

- appropriate avalanche safety programs where winter harvesting may expose workers to avalanches, providing guidance for the scheduling of winter operations to identify, control, or avoid unacceptable risks; and
- the need to identify areas where avalanches may occur after forest harvesting, with the potential to damage timber or other resources, or to interfere with reforestation.

The handbook employs a risk-based approach. A planning matrix is developed that combines the Canadian avalanche size system, which embodies concepts of vulnerability and consequence, with an estimate of the likelihood of avalanches (using three order-of-magnitude frequency classes) to produce a risk ranking system.

Some operators working in avalanche-prone terrain in British Columbia have developed avalanche risk management programs to proactively "manage with residual risk," a subtle difference from the traditional risk-avoidance approach. A key challenge has been to establish risk management objectives to provide guidance for avalanche practitioners employed by forest companies.

Assessing snow-avalanche risk on harvestable terrain

KEVIN STITZINGER, PETER WEISINGER, AND DAVID MCCLUNG

Each winter there are more than 300 000 avalanches ≥ size 2 (based on the Canadian Classification System) in the mountains of western Canada, 80% of which occur in the Coast and Columbia Mountains of British Columbia. Virtually all of these avalanches occur in forested zones where tree removal can uncover terrain prone to snow avalanche initiation and where existing avalanche paths can be laterally and longitudinally extended if adjacent tree cover is lost.

Our poster will present information on the progress of two current graduate studies from the University of British Columbia's Avalanche Research Group. The goal of both studies is the development of risk-based methods to aid decision-making when harvesting in avalanche-prone terrain. One study focuses on identifying terrain prone to avalanche initiation and estimating risk prior to logging; the second study focuses on issues of risk management where runout zones enter harvestable terrain. The poster will highlight methods and preliminary results.

Identification of natural and logging-related landslides in the Capilano River basin (coastal British Columbia): A comparison between remotely sensed survey and field survey

FRANCESCO BRARDINONI

In the Pacific Northwest, landslide inventories are routinely compiled by means of aerial photo interpretation. When examining photo pairs, the forest canopy, notably in old-growth forest, hides a population of "not-visible" landslides. The present study attempts to estimate the contribution of landslides not detectable from aerial photographs, to the global mass of sediment production from mass failures on forested terrain of the Capilano River basin. To achieve this, aerial photo interpretation has been coupled with intensive fieldwork for identification and measurement of all landslides. In order to minimize bias in the comparison and integration of field-collected and air photo–collected data, it was decided to define a 30-year time window. Results show that not-visible landslides can represent up to 85% of the total number of failures and can account for up to 30% of the total volume of debris mobilized. Rate of sediment production differs greatly (one order of magnitude) between two sub-basins of the study area, suggesting that such figures should be generalized with care within a physiographic region—Pacific Ranges of the Coast Mountains. Discrepancies in denudation rate are explained qualitatively by GIS-based analysis of slope frequency distributions, drainage density, and spatial distribution of surficial materials.

APPENDIX 2 Extended abstracts, posters, slide presentations, draft papers, and field trip guides*

This appendix contains supplementary material from the workshop, including extended abstracts, posters, slide presentations, draft papers, and field trip guides. The material is presented in the form of Portable Document Files (PDF). The resolution of the images in these files is variable, depending on the quality of images provided by the author, and the file format in which the original material was created.

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* Appendix 2 materials as supplied by individual presenters – not reviewed or edited (CD on back cover).

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Mapping and Hazard Assessment of Large Deep-Seated Landslides in Forested Landscapes

TERRY ROLLERSON, JUNE RYDER, JOHN COYLE AND ZHONGYOU LU

ABSTRACT

Definitions and criteria for the landslide hazard ratings currently used in terrain stability mapping for forestry in British Columbia are strongly oriented toward shallow translational landslides, primarily the likelihood of initiation of debris slides and associated debris flows. However, deep-seated landslides, ranging from earthflows to slow slides in bedrock, are common in many parts of the province. We know that these can be accelerated or reactivated as a result of natural disturbances, such as climate change, seismic events and stream undercutting. Similar changes may result from forestry activities, but little is known about the potential effects of forest roads and/or various silvicultural practices. To date, deep-seated landslides have been rated by ad hoc adaptations of the existing terrain stability classification systems. Difficulties arising include mapping the extent of these features, classification of deep-seated landslides, assessment of current activity and assignment of hazard ratings.

We discuss these difficulties, propose standard terminology for describing landslide activity, define logical hazard interpretations, and present simple criteria and rationale for hazard ratings. We also suggest modifications to the symbology used in the B.C. Terrain Classification System to facilitate the description and classification of deep-seated landslides.

EXAMPLES OF TERRAIN SYMBOLS, SLOPE STABILITY CLASSES AND IMPLICATIONS

Terrain Symbols (examples)	*Landslide Type and State*	*Slope Stability Interpretation*	*Implications*
Ca/Rk-**F"e**	headward part of active earthflow (initiation zone)	**V** or **U**	High likelihood that forest harvesting will have adverse effects, i.e., effects resulting from increased rate of flow
Cjs-**F"u** LGjs-**F"u**	slumps: active or recent (i.e., clearly defined)	**V** or **U**	
Cumr-**Fe**	active earthflow, downslope	**V** or **U**	
Cu - **F1e** $\frac{\text{Mb}}{\text{Cur}}$ -**F1e**	earthflow (appears to be inactive)	**II** - **IV** or **S** to **P** depending on slope steepness	Very low to moderate likelihood that forest harvesting will have adverse effects, i.e., effects resulting from increased rate of flow
Cmr-**F2e**	earthflow (status unknown)	**III-IV**	
Cuar-**F3e**	active earthflow	**V** or **U**	High likelihood that forest harvesting will have adverse effects, i.e., effects resulting from increased rate of flow.

Note: Symbols for geological processes include subtypes -F1 (inactive), -F2 (status unknown) and -F3 (active).

Flowslides and drowned, buried forests at Halden Creek, northeastern British Columbia

MARTEN GEERTSEMA AND JOHN CLAGUE

ABSTRACT

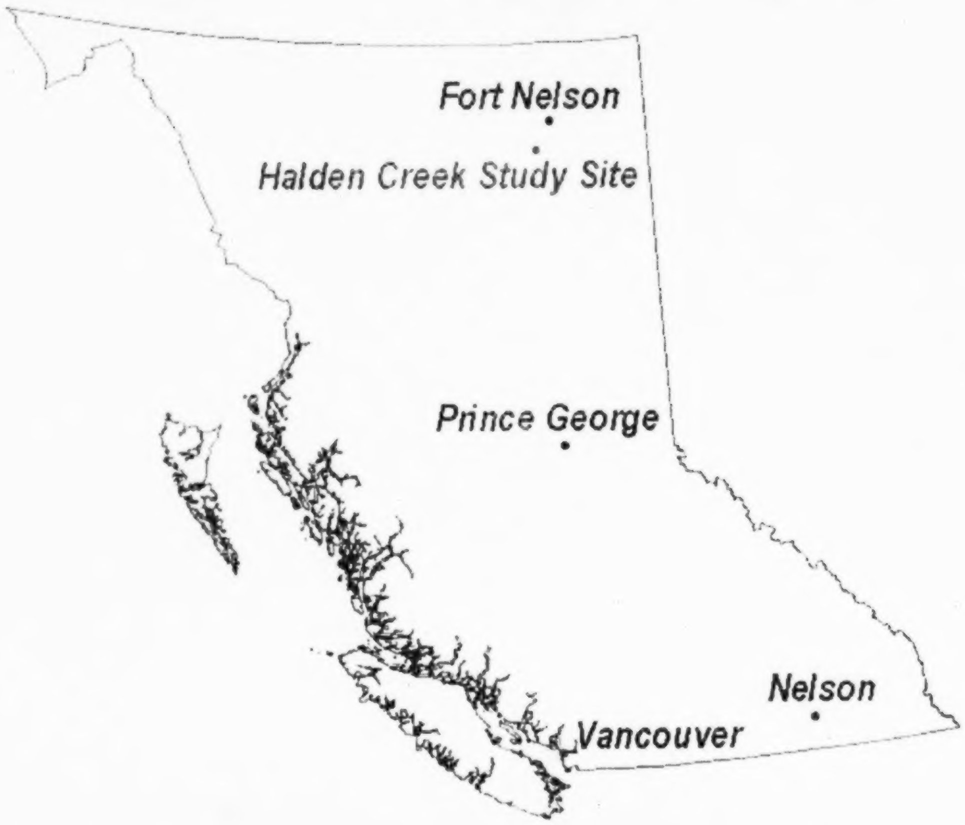
Halden Creek has been frequently impounded by flowslides. The landslides are recorded in sedimentary exposures in two ways: 1) Trees died in the resultant temporary lakes and were subsequently partially buried by alluvium. The buried portions of the trees were preserved. Bank erosion exhumed these ancient drowned forests. 2) In some cases multiple organic layers in eroded slide debris record separate flowslide events. Using radiocarbon dates of trees and organic layers, we attempt to reconstruct flowslide history at Halden Creek.

Flowslides and drowned, buried forests at Halden Creek, northeastern British Columbia

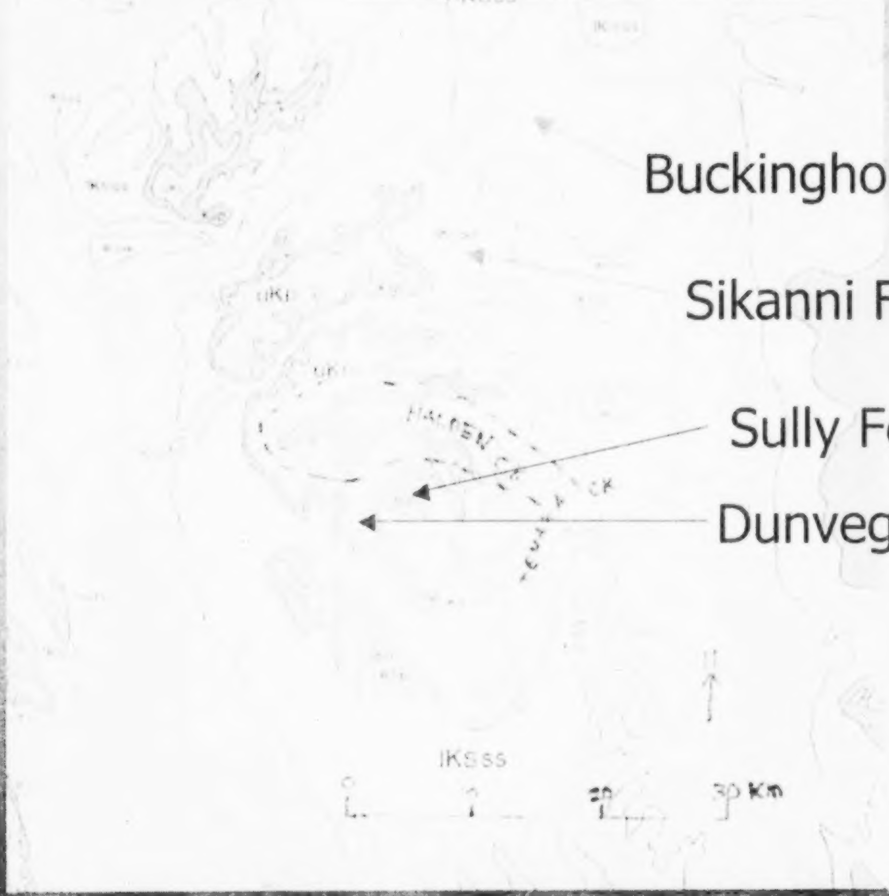
Marten [illegible]
BC Forest Se

John Clague
Simon Fraser University

Setting


Fort Nelson
Halden Creek Study Site
Prince George
Nelson
Vancouver

Setting


IKsss
IKsss
0
30 Km

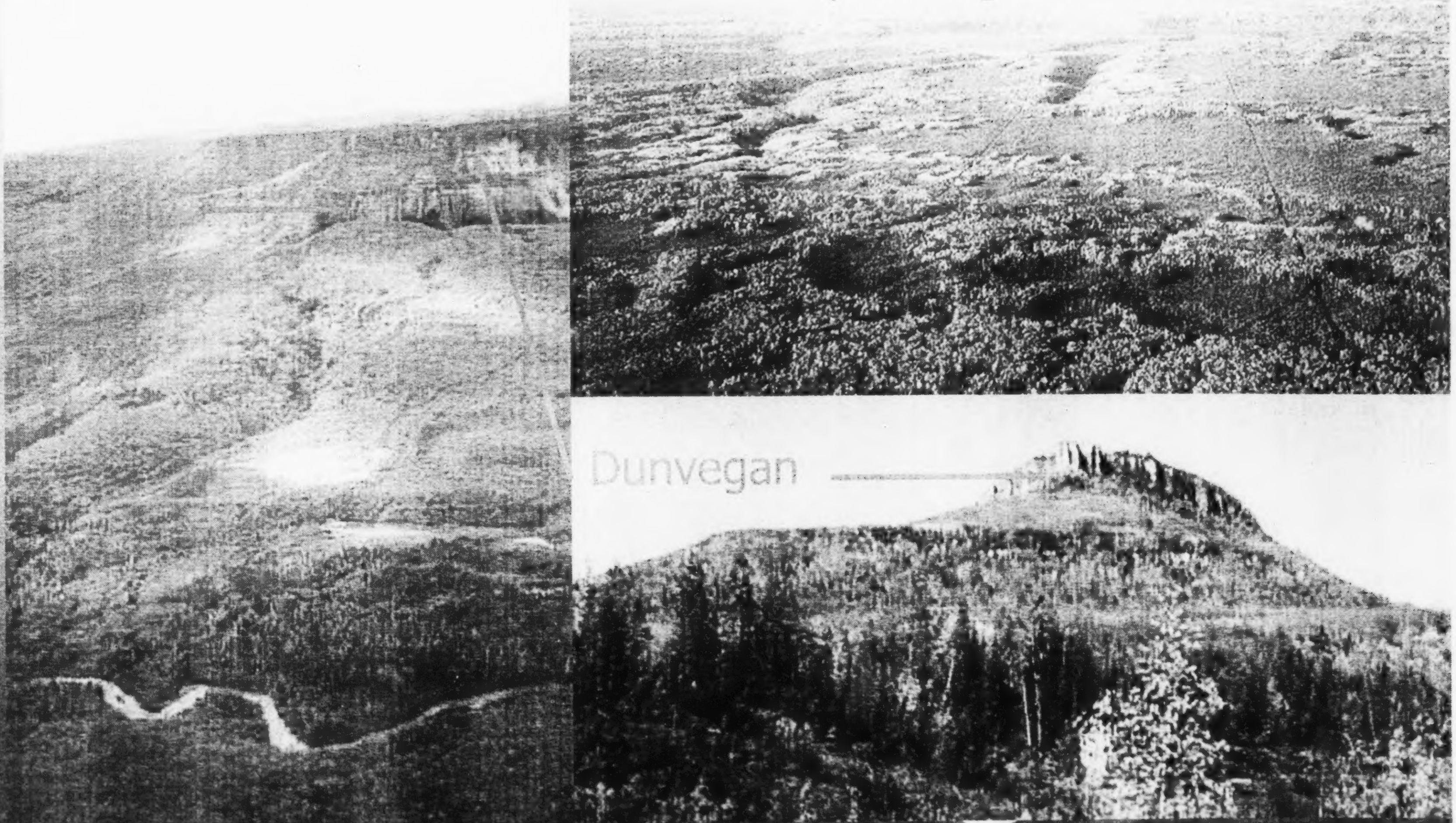
Buckinghorse Formation (marine shale)

Sikanni Formation (sandstone - shale)

Sully Formation (marine shale)

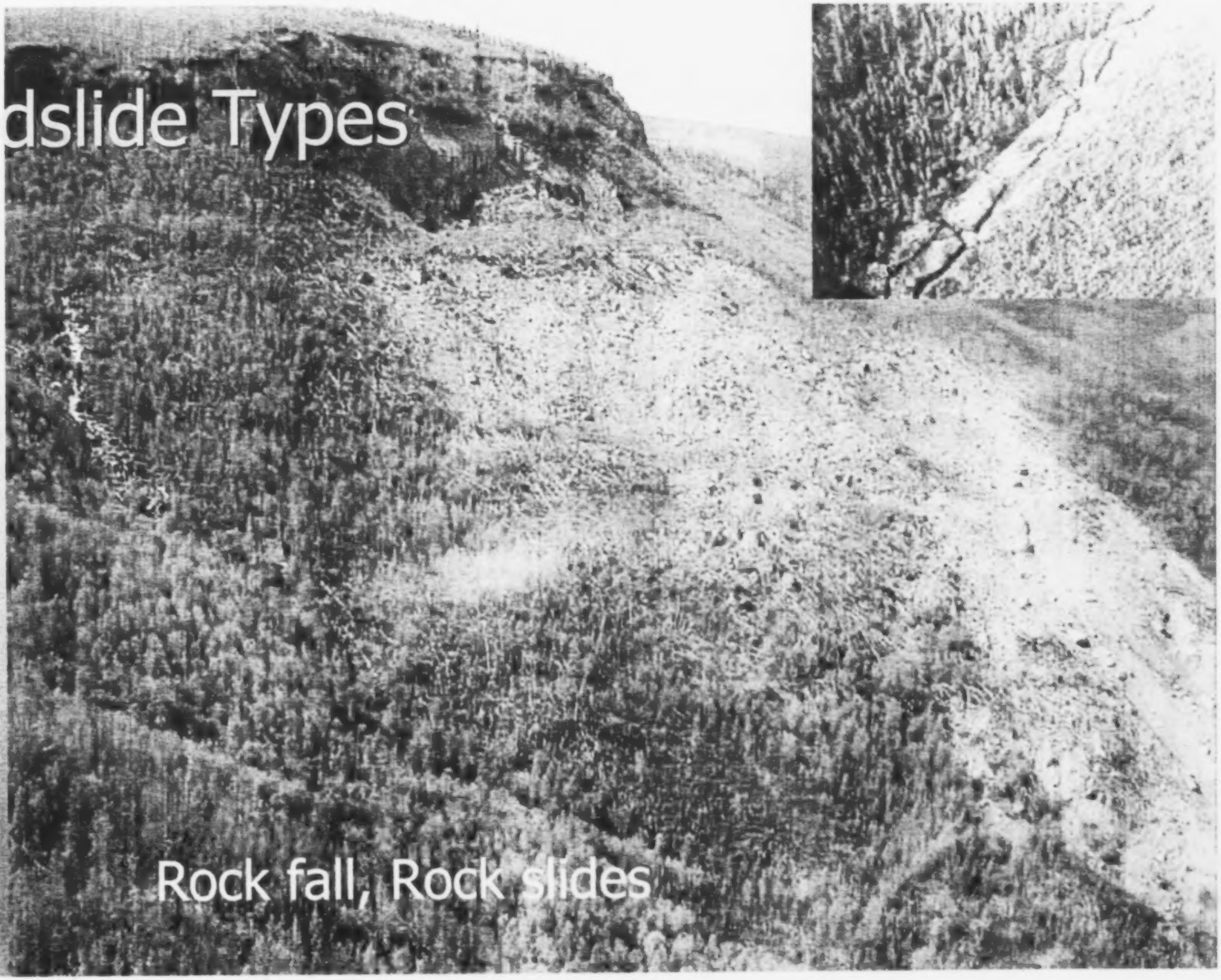
Dunvegan Formation (sandstone)

Setting


Fort Nelson Lowland
(Buckinghorse Formation)
Dunvegan

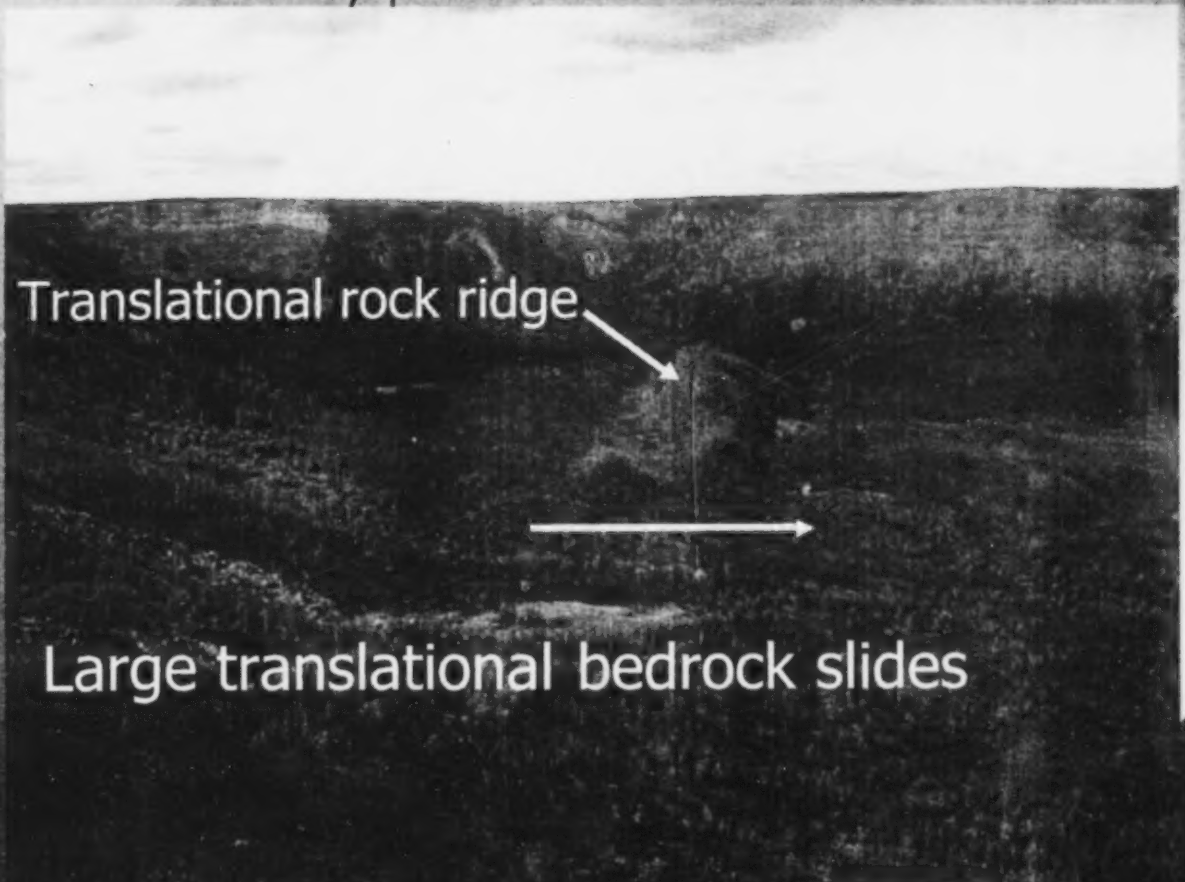
Setting

Landslide Types



Rock fall, Rock slides

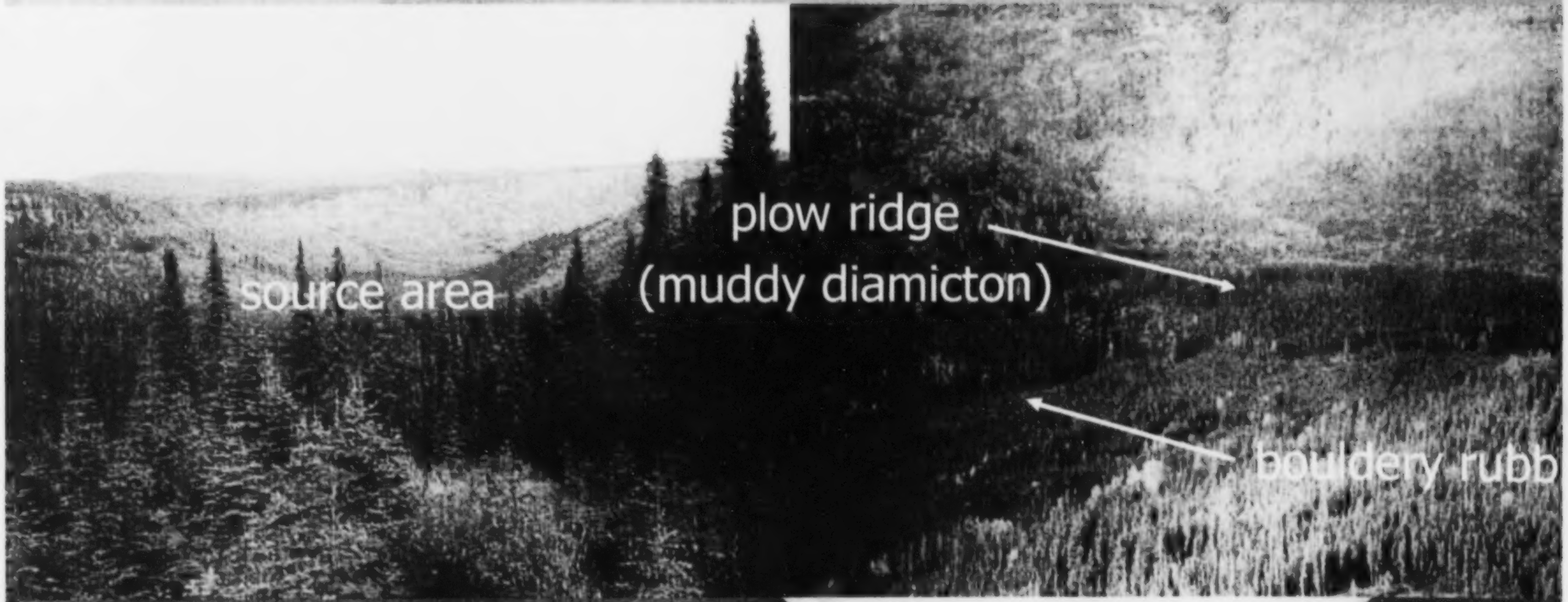
Landslide types



Translational rock ridge

Large translational bedrock slides

Landslide types


plow ridge
(muddy diamicton)
source area
bouldery rubb

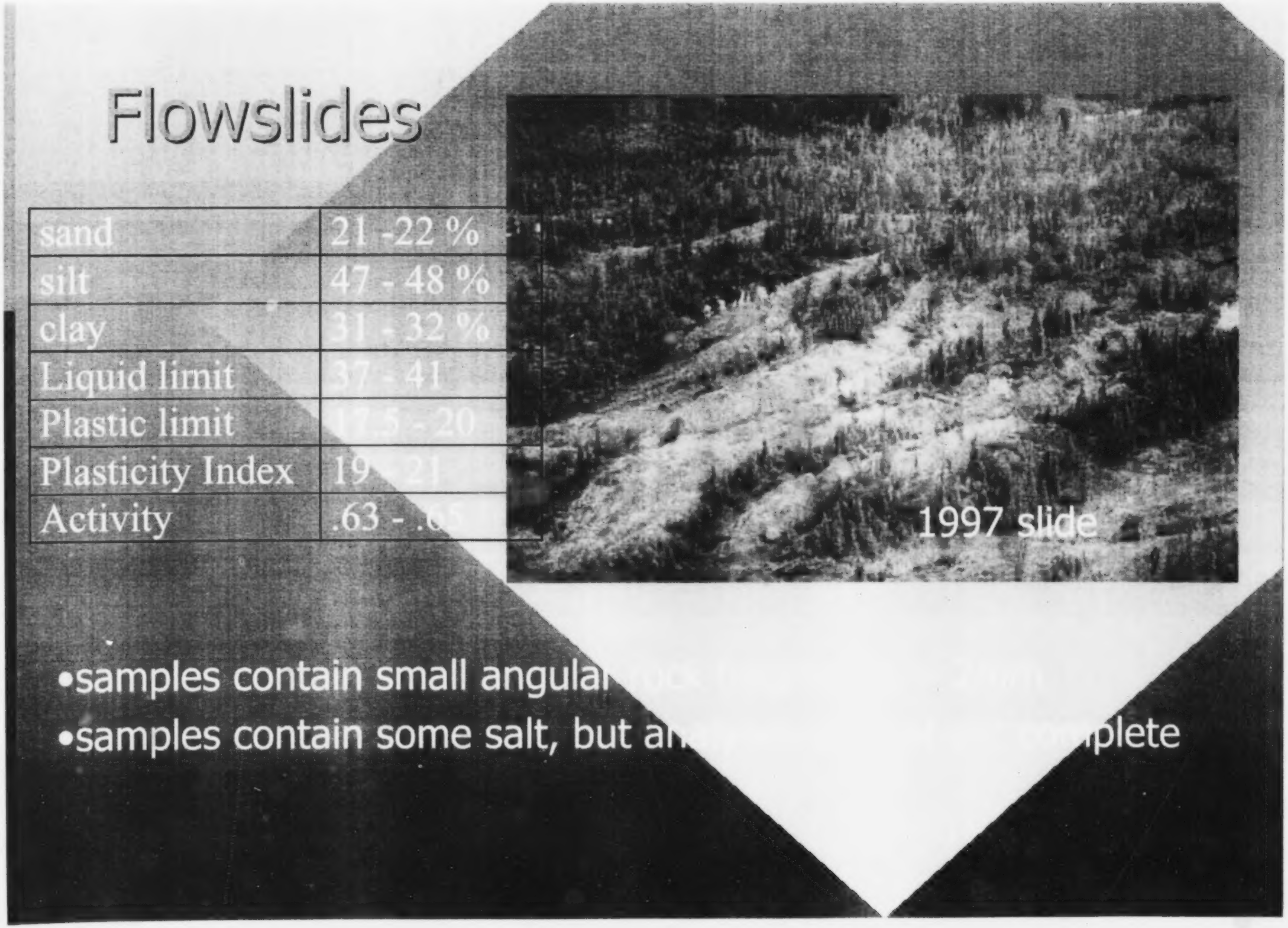
Low-angle rock flow (~ 4 kı

Landslide types

1997 slide

Low-angle flowslides

(in muddy, low clast content diamic



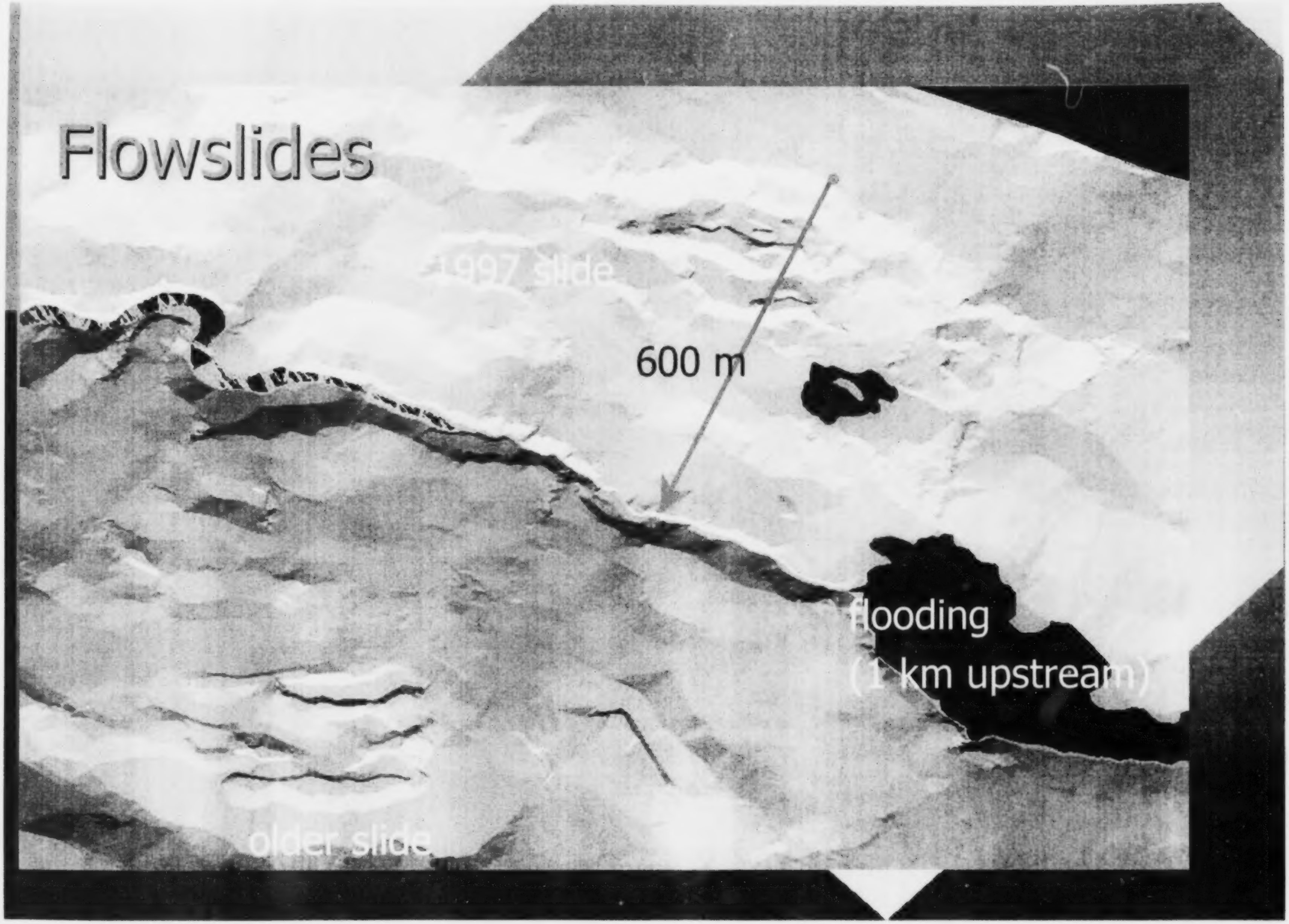
Flowslides

sand	21 -22 %
silt	47 - 48 %
clay	31 - 32 %
Liquid limit	37 - 41
Plastic limit	17.5 - 20
Plasticity Index	19 - 21
Activity	.63 - .65

1997 slide

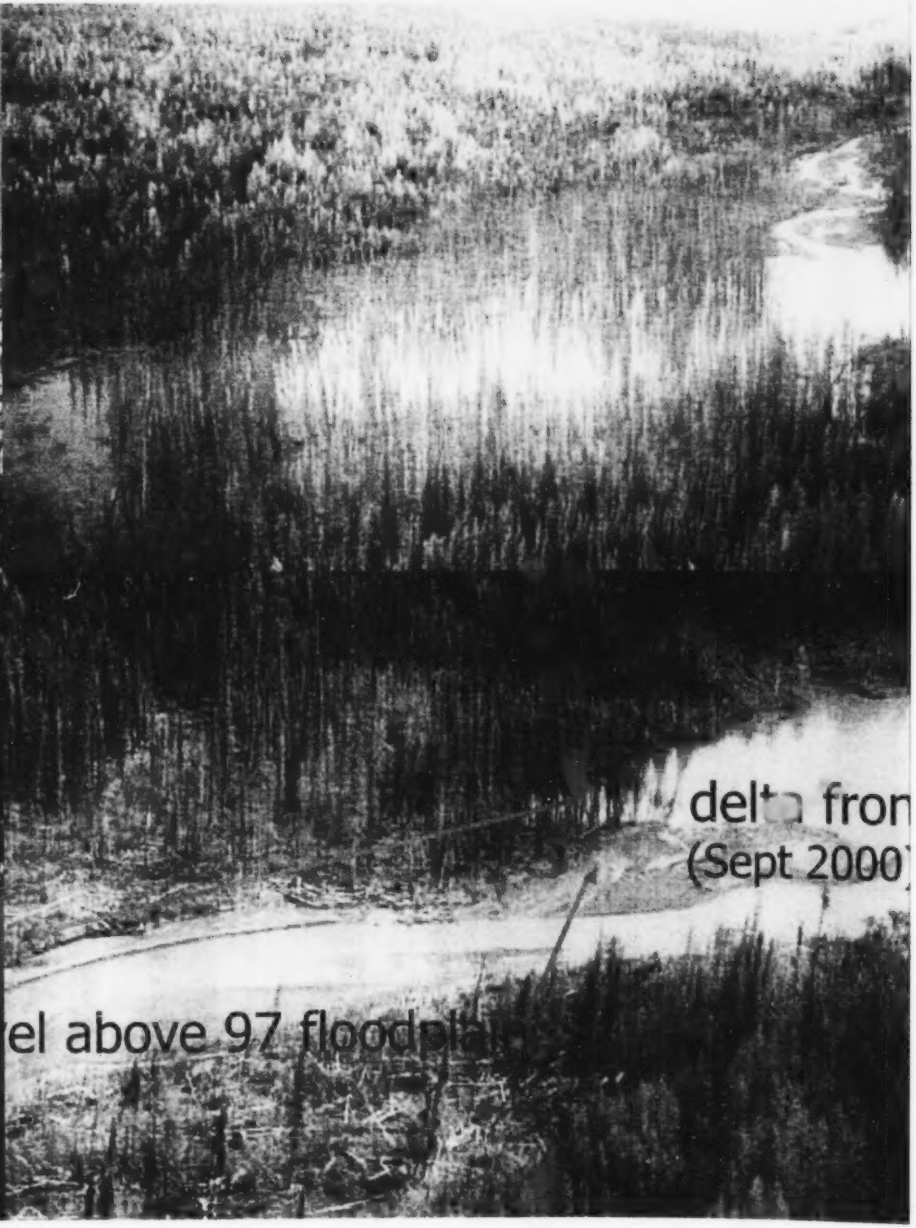
- samples contain small angular rock [illegible]
- samples contain some salt, but an [illegible] complete

Flowslides


1997 slide
600 m
flooding
(1 km upstream)
older slide

Drowned Forests

997 impoundment


delt[illegible] fron
(Sept 2000)

mud up to 7 m above delta top

3 m of sand and pebble gravel above 97 floodplain

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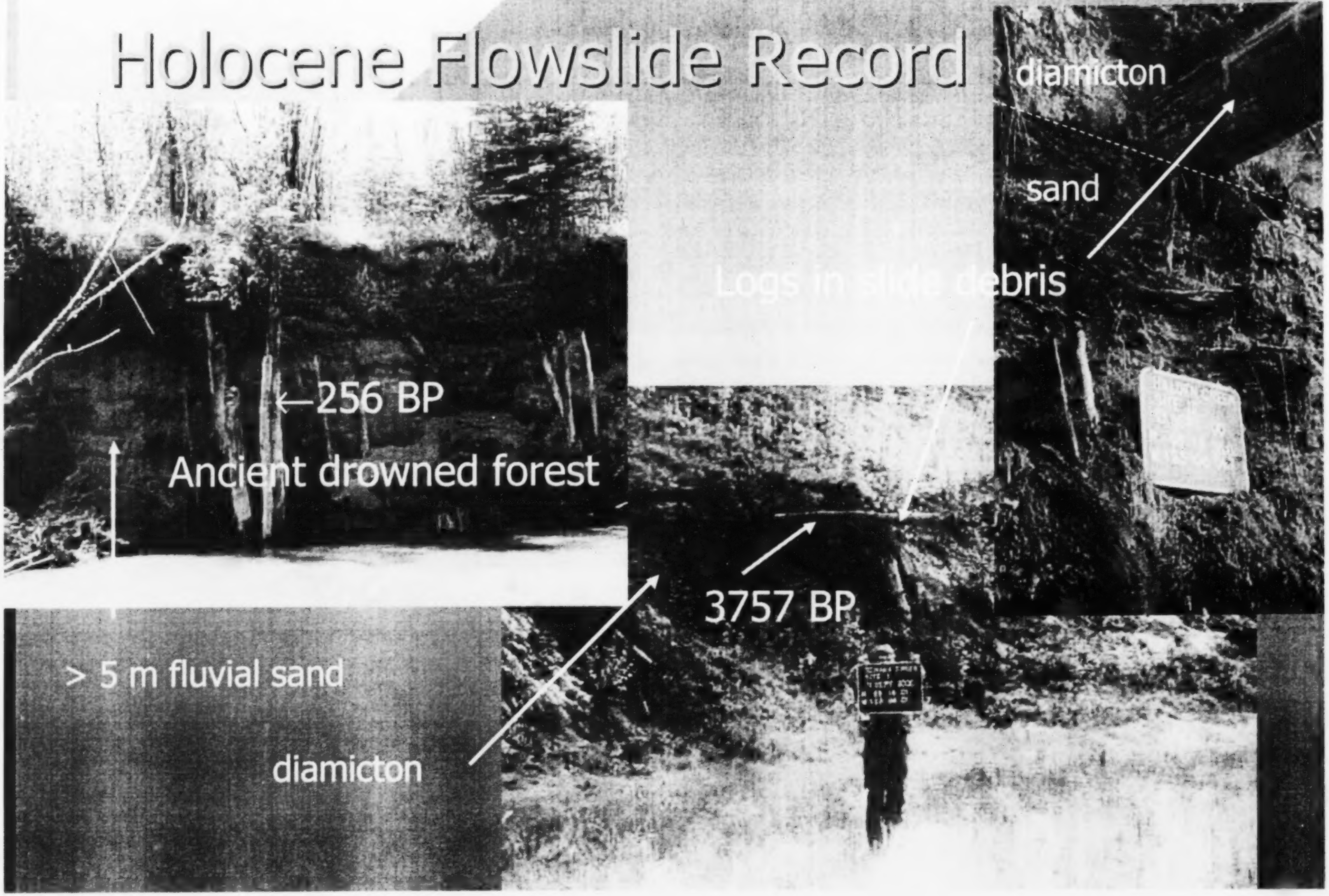
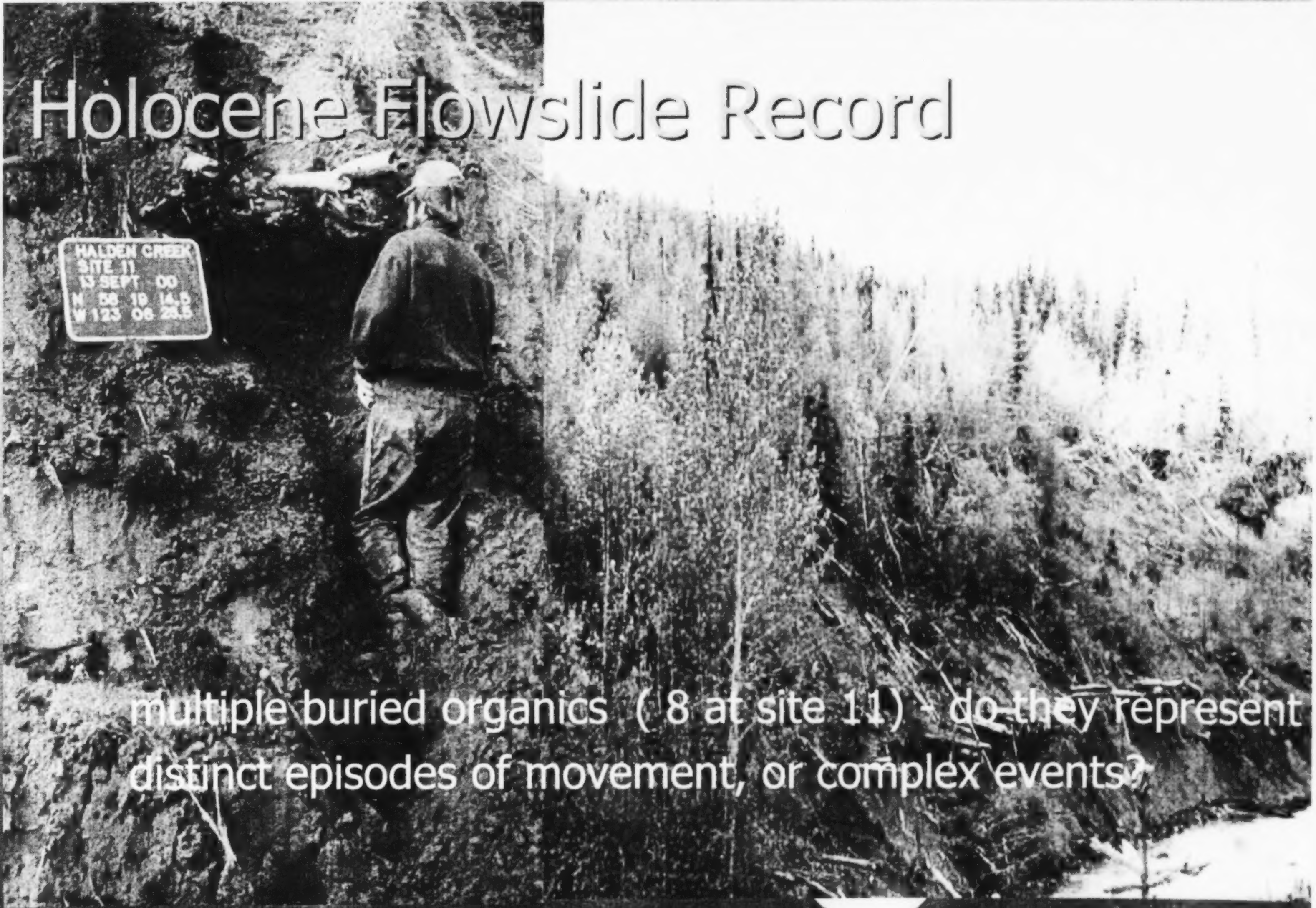
Holocene Flowslide Record


diamicton
sand
Logs in slide debris
←256 BP
Ancient drowned forest
3757 BP
> 5 m fluvial sand
diamicton

Holocene Flowslide Record


HALDEN CREEK
SITE 11
13 SEPT 00
N 56 19 14.5
W 123 06 28.5

- multiple buried organics (8 at site 11) - do they represent distinct episodes of movement, or complex events?

Implications

Slope hazards and silviculture

Should we invest here?

Implications

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BC Forest Service, Prince George Region

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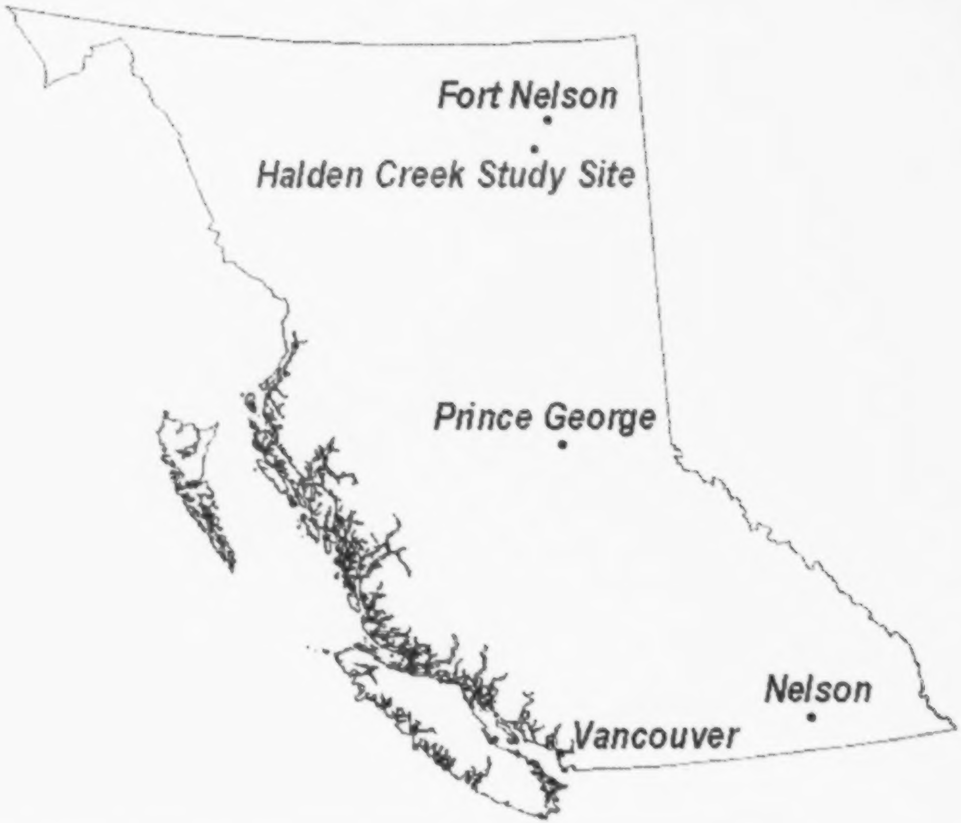
Fort Nelson
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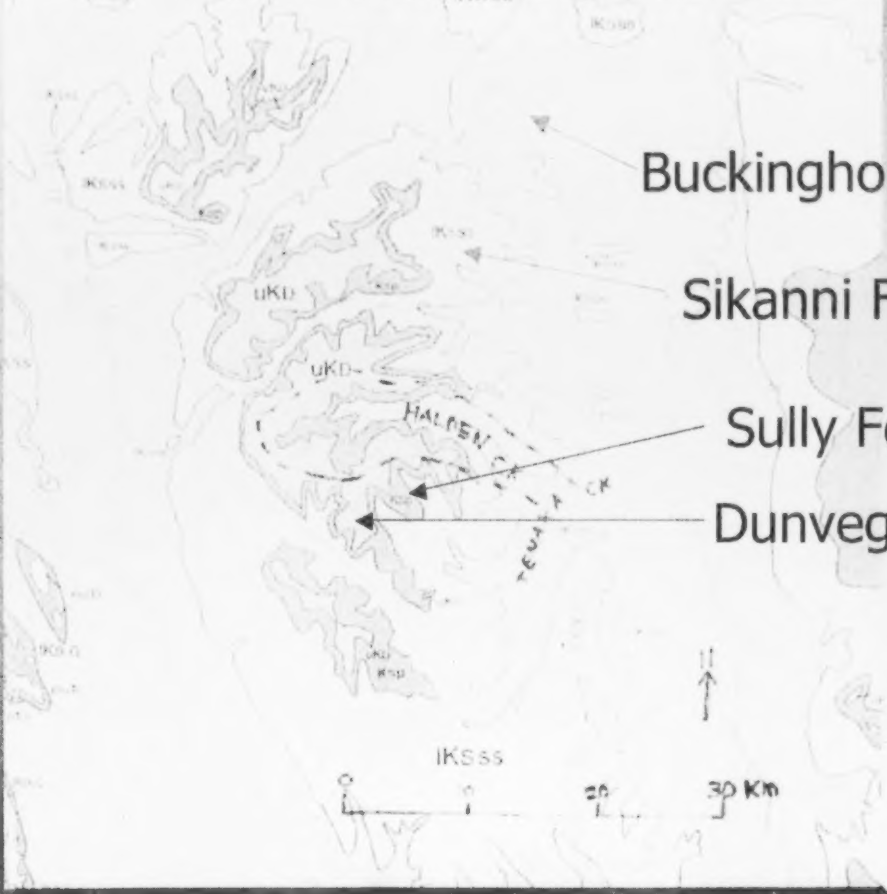
Setting


uKD
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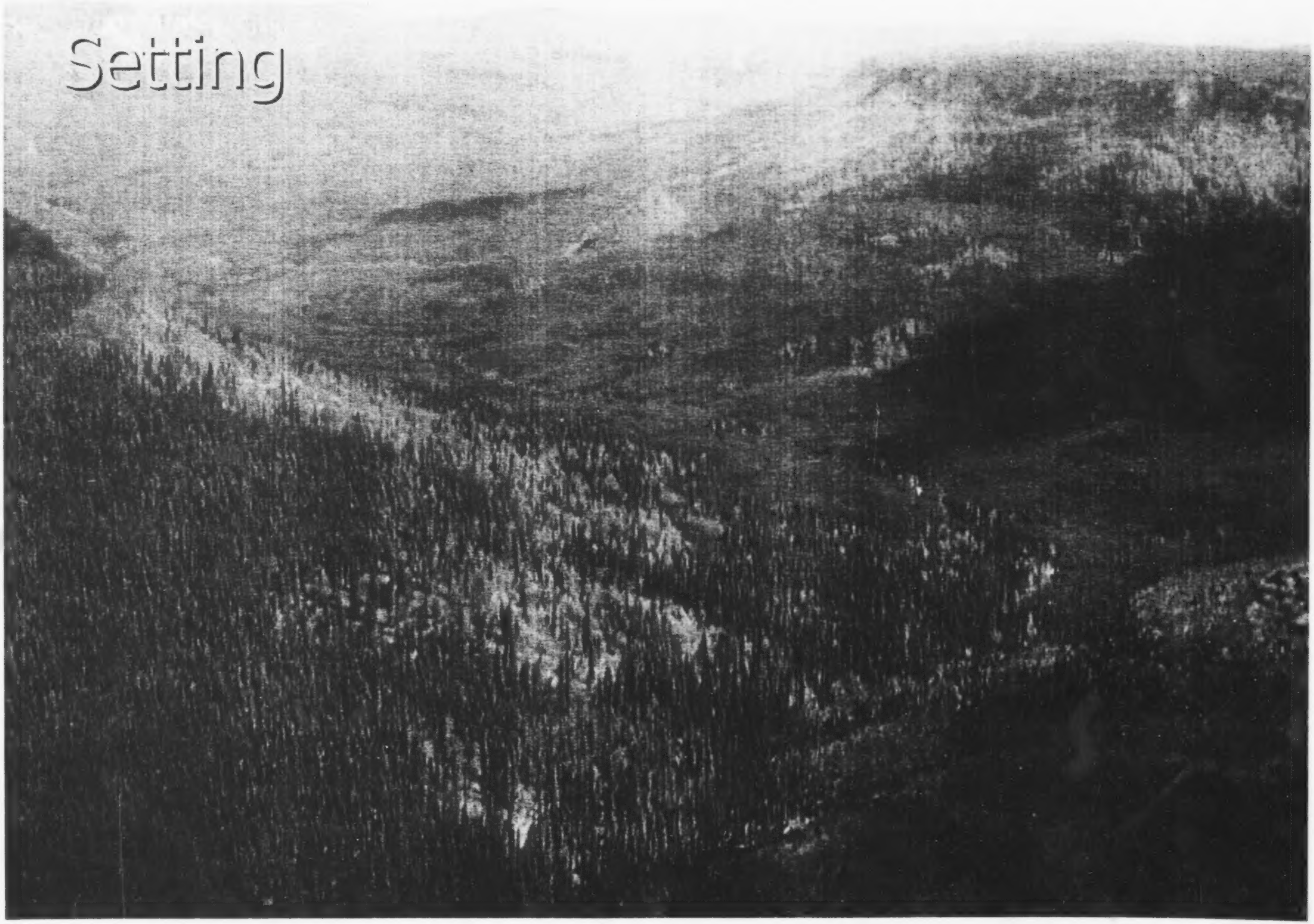
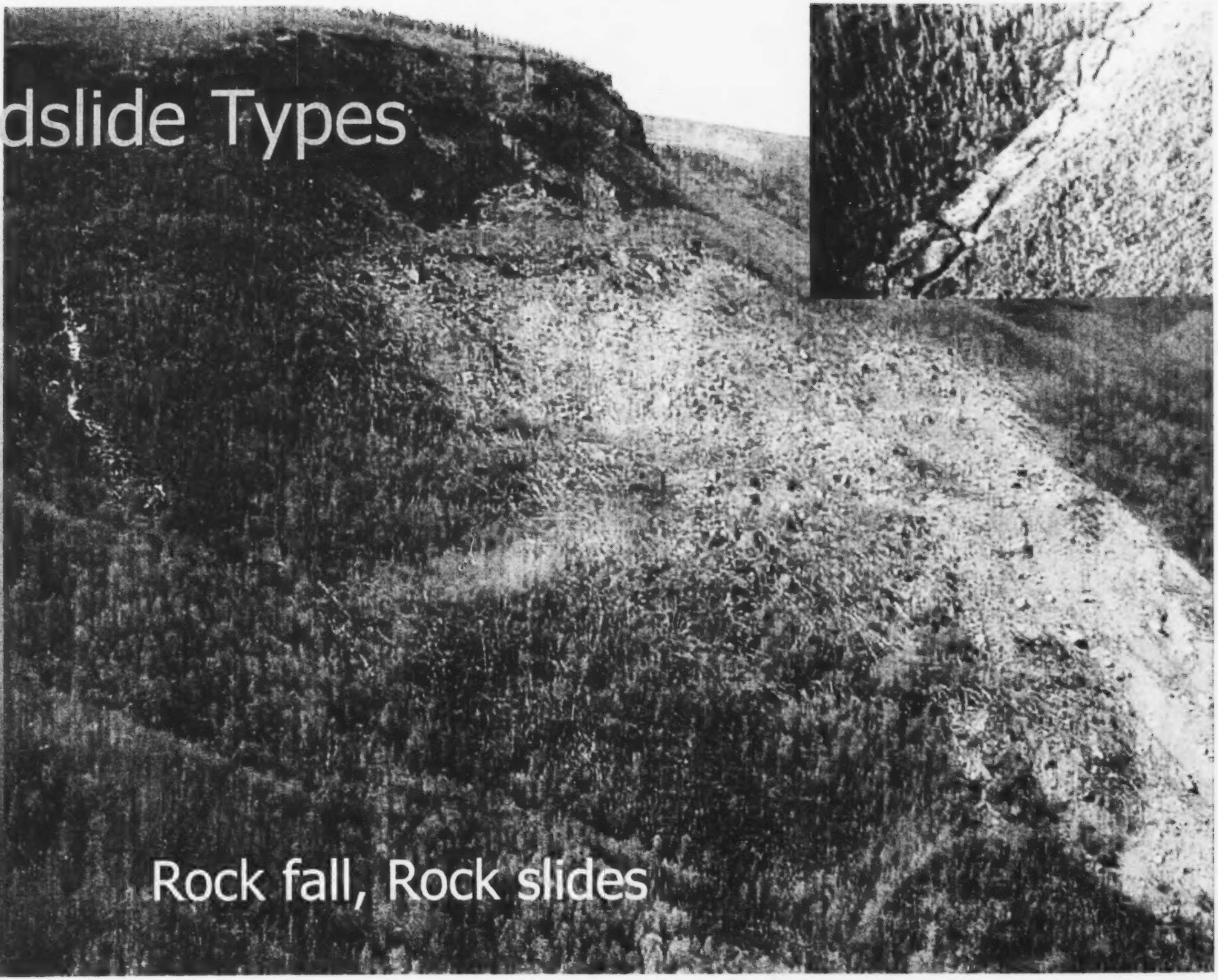


Setting

Landslide Types



Rock fall, Rock slides

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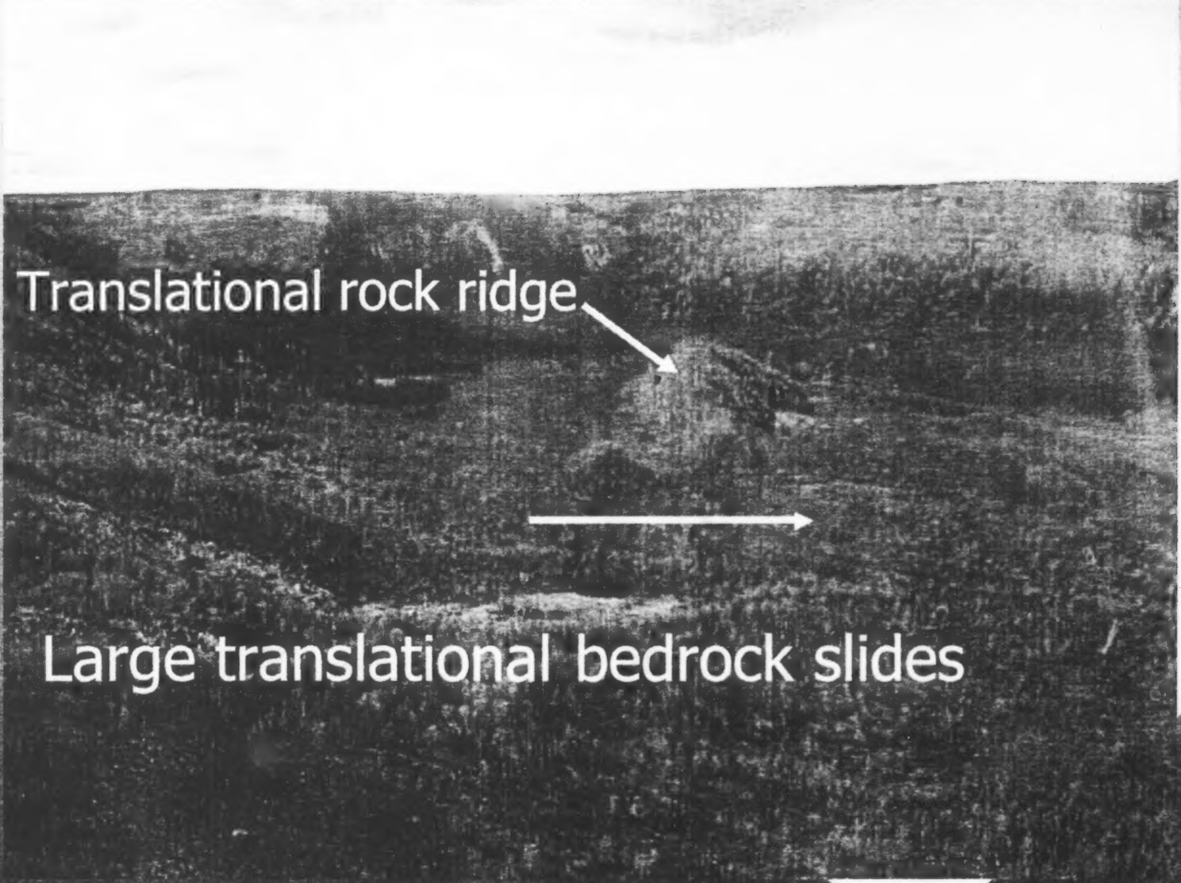
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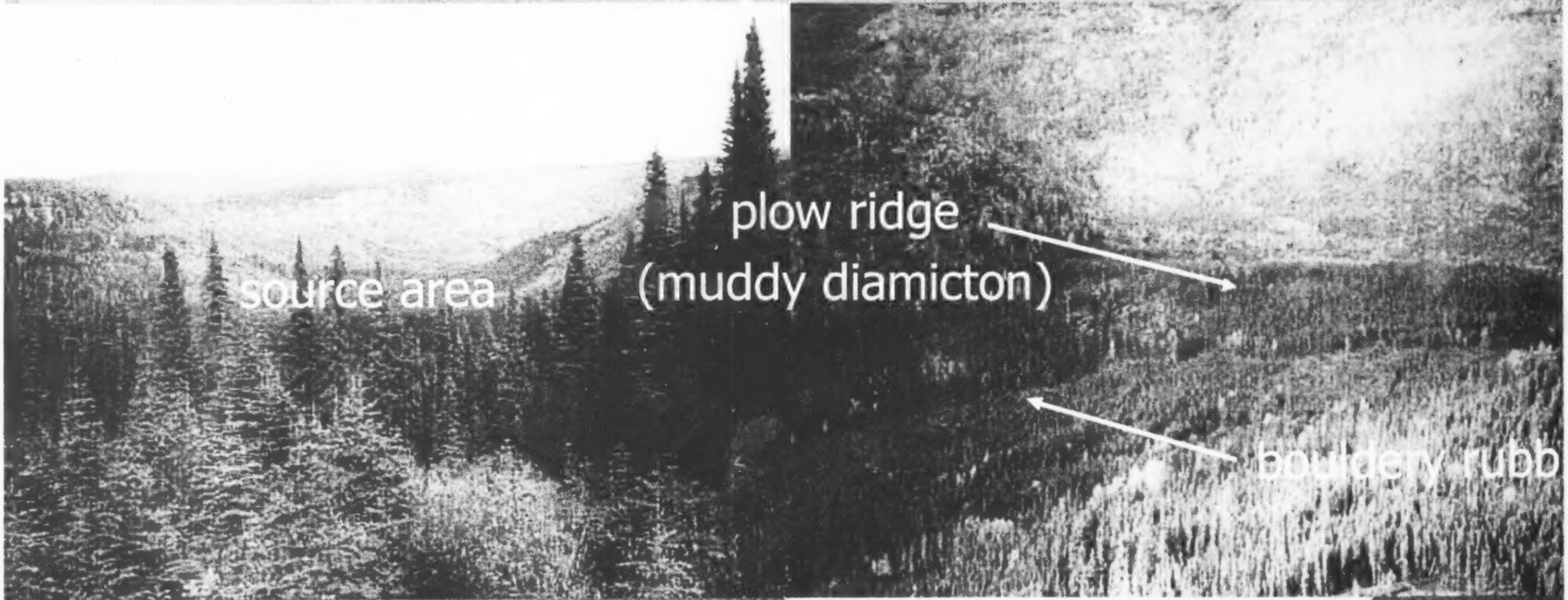
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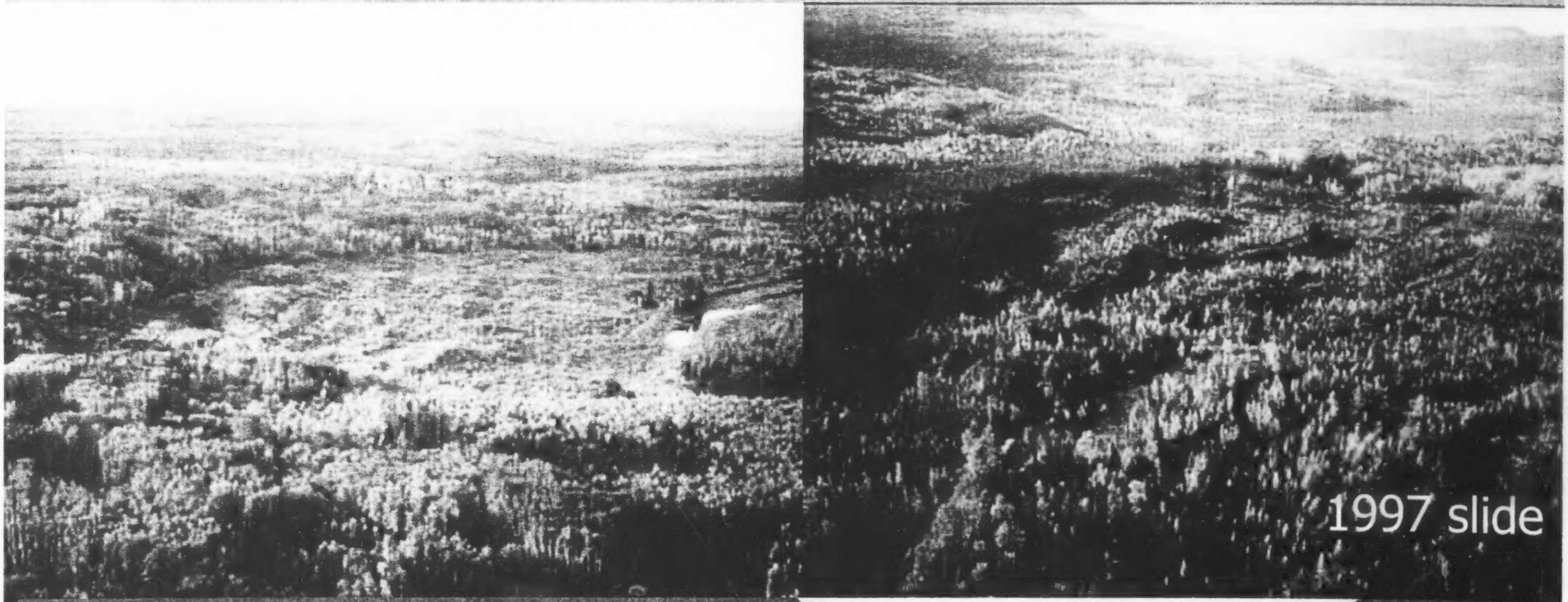
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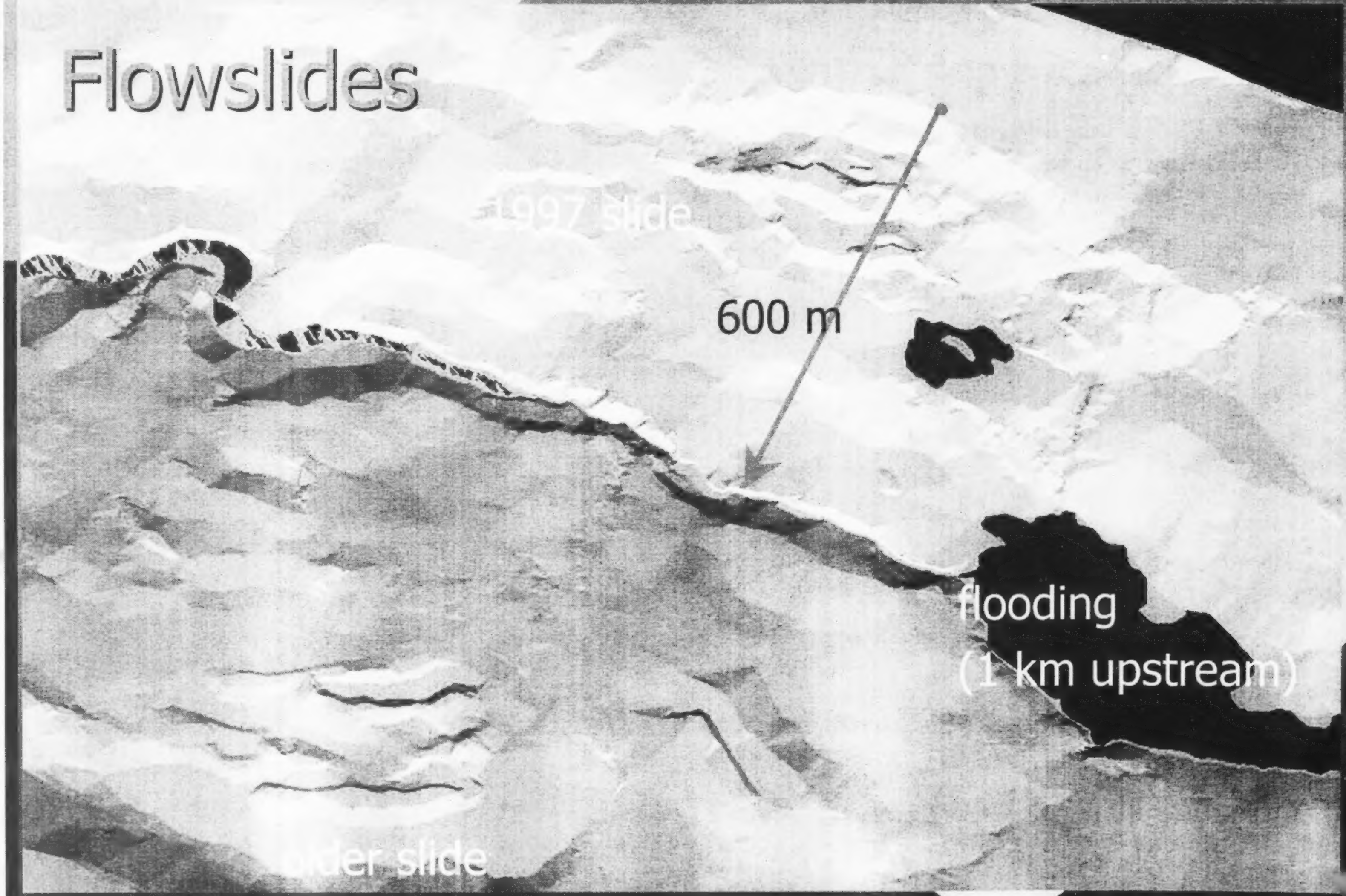
1997 slide
600 m
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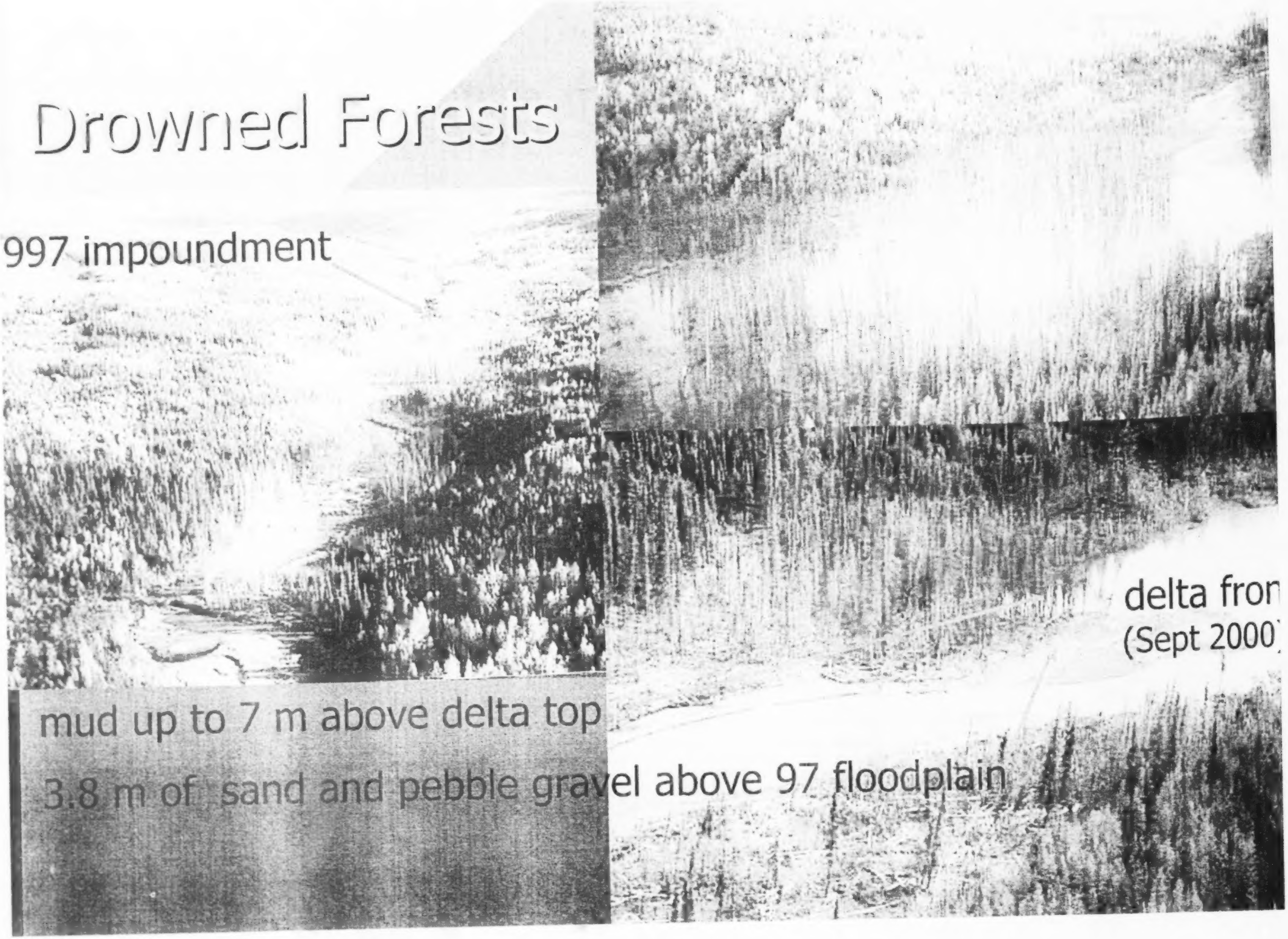
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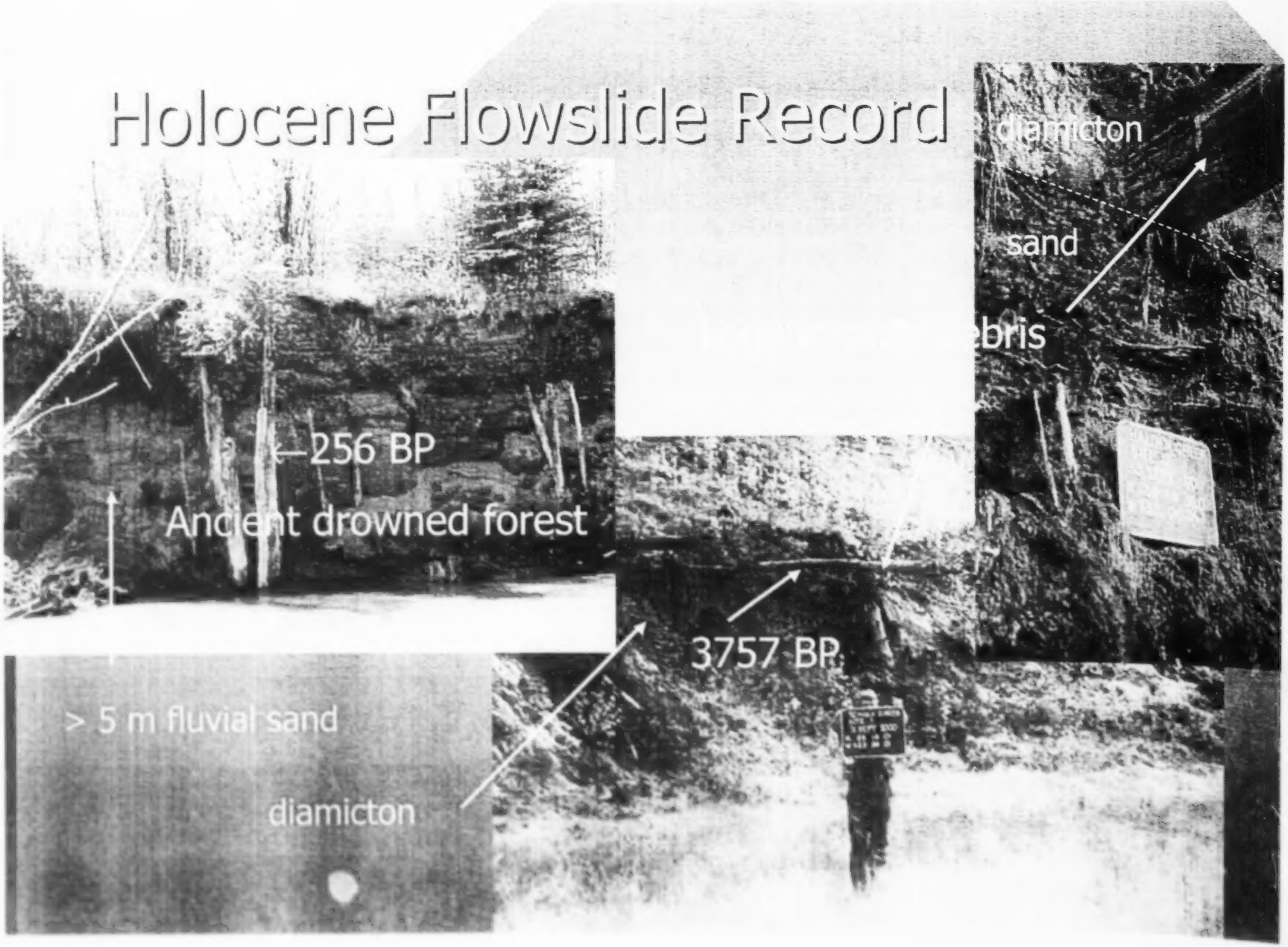
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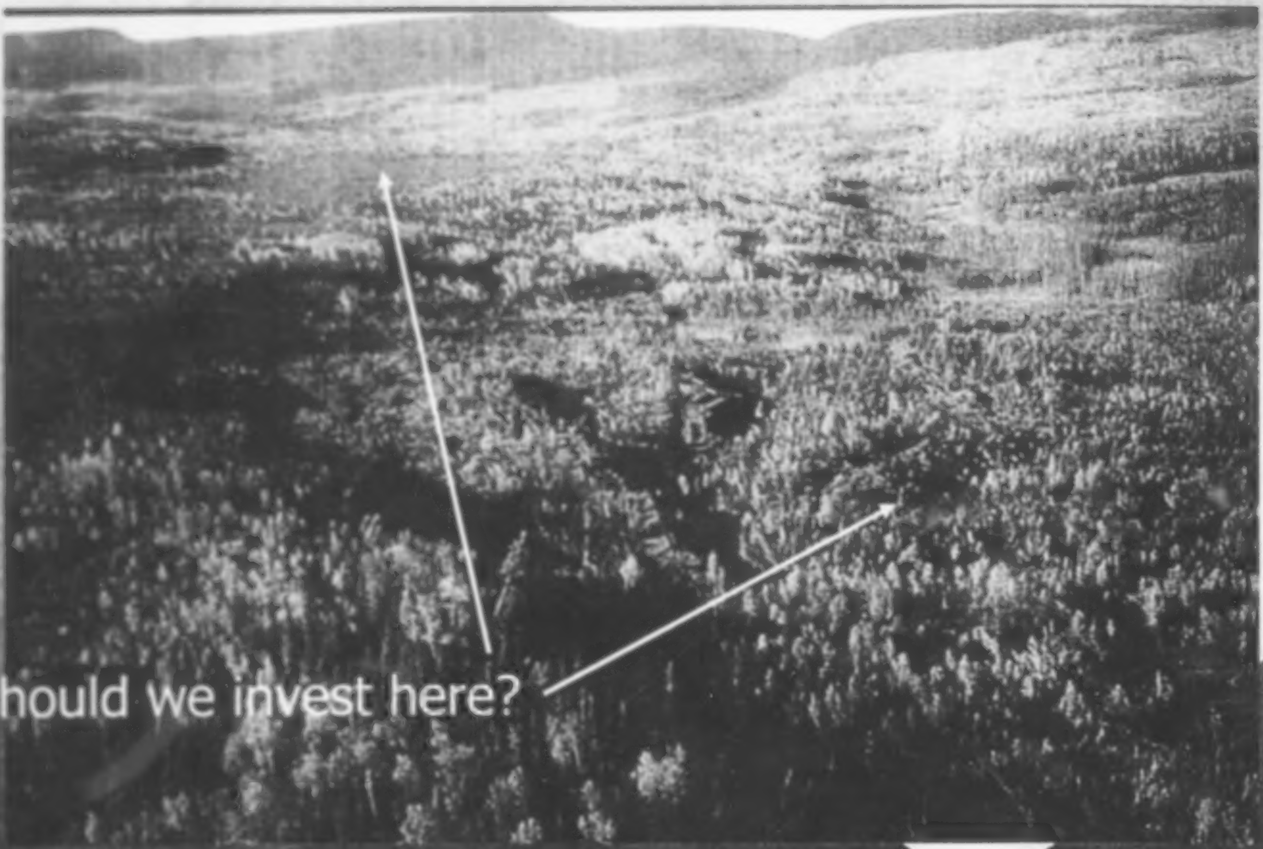


Should we invest here?

Implications

Slope hazards and silviculture

Should we invest here?

HOW "RISKY" ARE OLD ROADS?

Mike Murrell, P.Geo.

Squamish Forest District, 42000 Loggers Lane, Squamish, BC V0N 3G0

In 1998 the Squamish Forest District was faced with the daunting task of systematically and economically creating an inventory of all forest roads and associated potential stability problems in the District. The main purpose was to identify and prioritize obvious hazardous non-used road sections that could put people or the environment at risk. If funding could be subsequently raised, stabilization via road deactivation could be carried out commencing with the roads of highest **Risk**.

A **Risk Assessment** method was developed in Squamish to rapidly and economically identify and quantify the environmental risks of road sections by examining them for visual signs of deterioration and considering the probable consequences to:

1. people (human factor)
2. the fish (in stream factor) and
3. the forest (upslope factor)

By visually identifying and quantifying both the hazard and the probable consequences, a simple calculation can produce a numerical **Risk** and a subsequent ranking of all identified potential landslides. Although this reconnaissance method is limited to roads that are not completely overgrown or canopied, it quickly allows the screening of extensive road systems to help establish priority areas regardless of the tenure situation.

The method involves flying slowly at low elevation over the roads to recognize signs of potential road instability, then judging what and when an "Event" could occur (i.e. the **Hazard**) followed by a judgement of what the damage would likely occur to each of three "Factors" (i.e. the **Consequence**). The Hazard and Consequences are quantified by using a chart of increasing magnitude. Five numbers are entered into a spreadsheet that computes, rationalizes and combines the resultant risks and produces a mini-graph for each identified road section. The graphs are then pasted onto a 1:50,000 base map for display and communication purposes.

Decision Makers can use the spreadsheets and maps as a tool to assist in the planning and justification of subsequent road deactivaton work. Contrarily, it helps them decide if a road section's Risk is too low to warrant work - i.e. it has "Tolerable Risk".

Risk Management is nothing more than examining the Risk Assessment results and deciding on the appropriate action. For road deactivaion this can vary from "Do Nothing" to "Full Deactivation and Rehabilitation". Unacceptable Risk can be reduced to a tolerable level by altering one or more of the following:

1) the Source (i.e. the *Hazard*)
2) the Path, and/or
3) the Receptor (i.e. the *Consequence*)

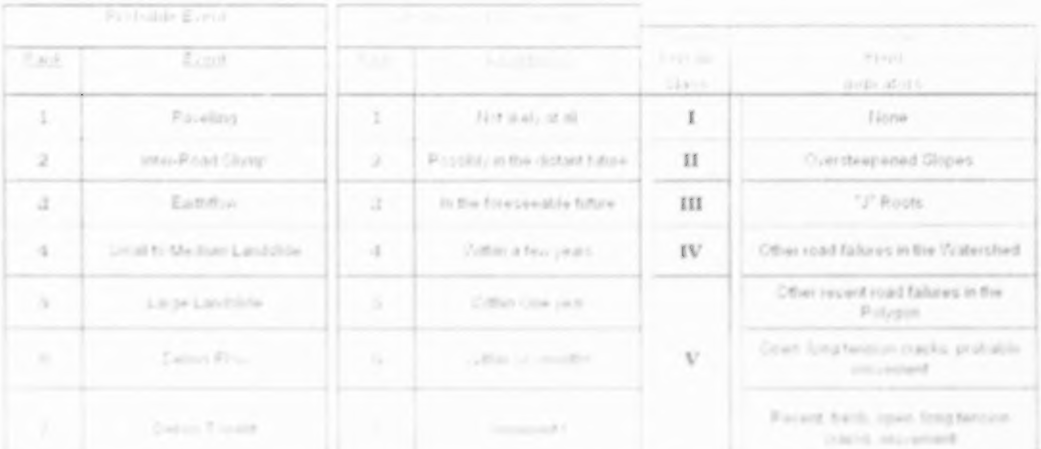
and can be explained by the "Tippling Rock" Scenario.

This talk presented the rationale leading to the present method, explained the method itself, and presented some of the results in the Squamish Forest District including portions of some the maps generated from the 1999 fieldwork.

The main slides from the presentation are attached below.

Note: This paper was presented at the Dec. 2000 Coastal Forest Site Rehabilitation Conference and subsequently published in the Watershed Restoration "Streamline" publication, Vol.5 No.3. It is available on the Internet at: http://srmwww.gov.bc.ca/frco/bookshop/streamline.html

Figures 3 to 6 below are provided courtesy of "Streamline"



Probable Event		[illegible]			
Rank	Event	Rank	Likelihood	[illegible] Class	Field Indicators
1	Ravelling	1	Not likely at all	I	None
2	Inter-Road Slump	2	Possibly in the distant future	II	Oversteepened Slopes
3	Earthflow	3	In the foreseeable future	III	"J" Roots
4	Small to Medium Landslide	4	Within a few years	IV	Other road failures in the Watershed
5	Large Landslide	5	Within one year	V	Other recent road failures in the Polygon
6	Debris Flow	6	Within six months		Open, long tension cracks, probable movement
7	Debris Torrent	7	Imminent		Recent, fresh, open, long tension cracks, movement

Figure 1. Identifying Hazard – The type of event and probable timing must be documented in the field.

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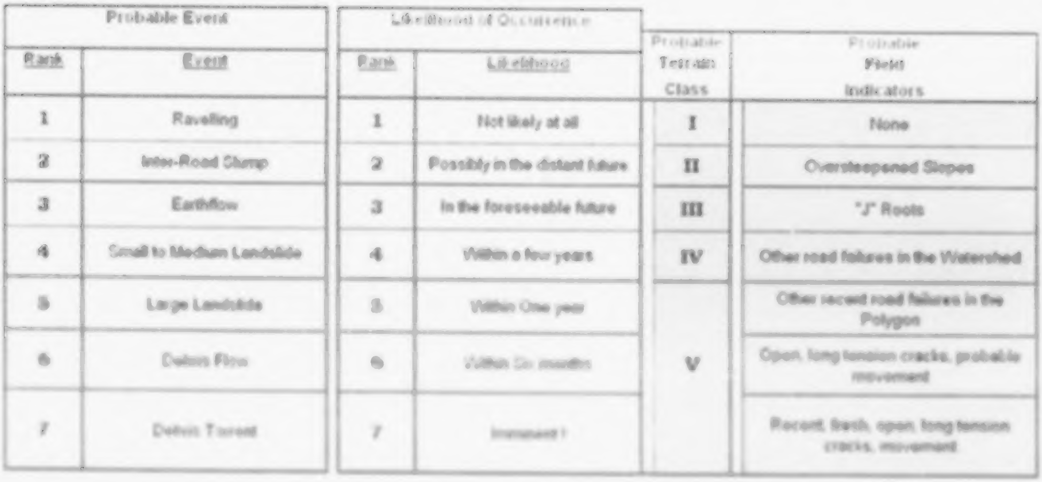

Probable Event		Likelihood of Occurrence		Probable Terrain Class	Probable Field Indicators
Rank	Event	Rank	Likelihood		
1	Ravelling	1	Not likely at all	I	None
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Figure 1. Identifying Hazard – The type of event and probable timing must be documented in the field.

Identifying "Consequence"

Chart "C" | Chart "D" | Chart [illegible]

The Human Factor (Human Life)		The Instream Factor (The Fish Habitat)		The Upslope Factor (The Forest)	
Rank	Consequence	Rank	Consequence	Rank	Consequence
0	No effect	0	No effect	0	No effect
1	Minor effect- (Visual Eyesore)	1	Minor silt into an S5 or S6 stream >250 m from fish bearing waters	1	Affects a NON-PRODUCTIVE or a NON-COMMERCIAL cover
2	One Person inconvenienced (e.g. A hiker isolated)	2	Minor silt into an S5 or S6 stream <250 m from fish bearing waters	2	Affects a NON-FREEGROWING stand < 0.25ha
3	Many People Inconvenienced (e.g. Vehicle(s) isolated)	3	Partial or full blockage of an S5 or S6 stream >500m from fish bearing waters	3	Affects a NON-FREEGROWING stand > 0.25ha
4	Low volume road/trail at risk. Possibility of Minor Injuries	4	Partial blockage of an S5 or S6 stream <500 m from fish bearing waters	4	Affects a FREEGROWING stand < 0.25 ha
5	Low volume road/trail AND/OR Cabin/Campsite at risk. Possibility of Moderate Injuries	5	Full blockage of an S5 or S6 stream <500 m from fish bearing waters	5	Affects a FREEGROWING stand > 0.25 ha
6	Medium volume road/trail at risk. Possibly one Person Severly Injured	6	Partial blockage of a resident fish bearing stream	6	Affects an IMMATURE stand < 0.5 ha
7	Medium volume road/trail AND/OR house/campground at risk. Possibly > One Person Severly Injured	7	Full blockage of a resident fish bearing stream	7	Affects an IMMATURE stand > 0.5 ha
8	High volume road/trail AND/OR house/campground at risk. Possibly One Person Killed	8	Partial blockage of a salmon bearing stream OR short term impact (<3 day shutdown) to a community watershed	8	Affects a MATURE stand < 1.0 ha
9	High volume road/trail AND/OR Subdivision at risk. Possibility of > One Person Killed	9	Full blockage of a salmon bearing stream OR longer term impact (>3 day shutdown) to a community watershed	9	Affects a MATURE stand > 1.0 ha

Figure 2. Identifying Consequence – If the Hazard becomes an "Event", what damage could it do to: 1) Humans, 2) Fish habitat and 3) the Forest environment?

Weighting Factors: Human Factor: 1 Instream Factor: 1 Upslope Factor: 1				Highest Possible Raw Score with this Weighting = 243			
				1	2	3	4
EXAMPLE Calculated Hazard range 0 - 9	Assessed Consequence (see figure 6)			Calculated Risk			
	Enter Human Factor Consequence (0-9)	Enter Instream Factor Consequence (0-9)	Enter Upslope Factor Consequence (0-9)	Human Factor Score Max = 100	Instream Factor Score Max = 100	Upslope Factor Score Max = 100	Total Rationalized Score Max = 100
4.1	0	2	1	0	10	5	5
5.3	3	6	4	20	39	26	28
6.2	4	7	4	31	64	31	39
6.6	7	7	5	60	60	51	57
7.4	8	8	7	73	73	64	70
8.2	8	8	8	82	82	82	82
[illegible]	9	9	9	96	96	96	96

Figure 3. Calculating Risk – A spreadsheet calculates the Risk to Humans, Fish and Forest separately and rationalizes each to a "100" maximum score.

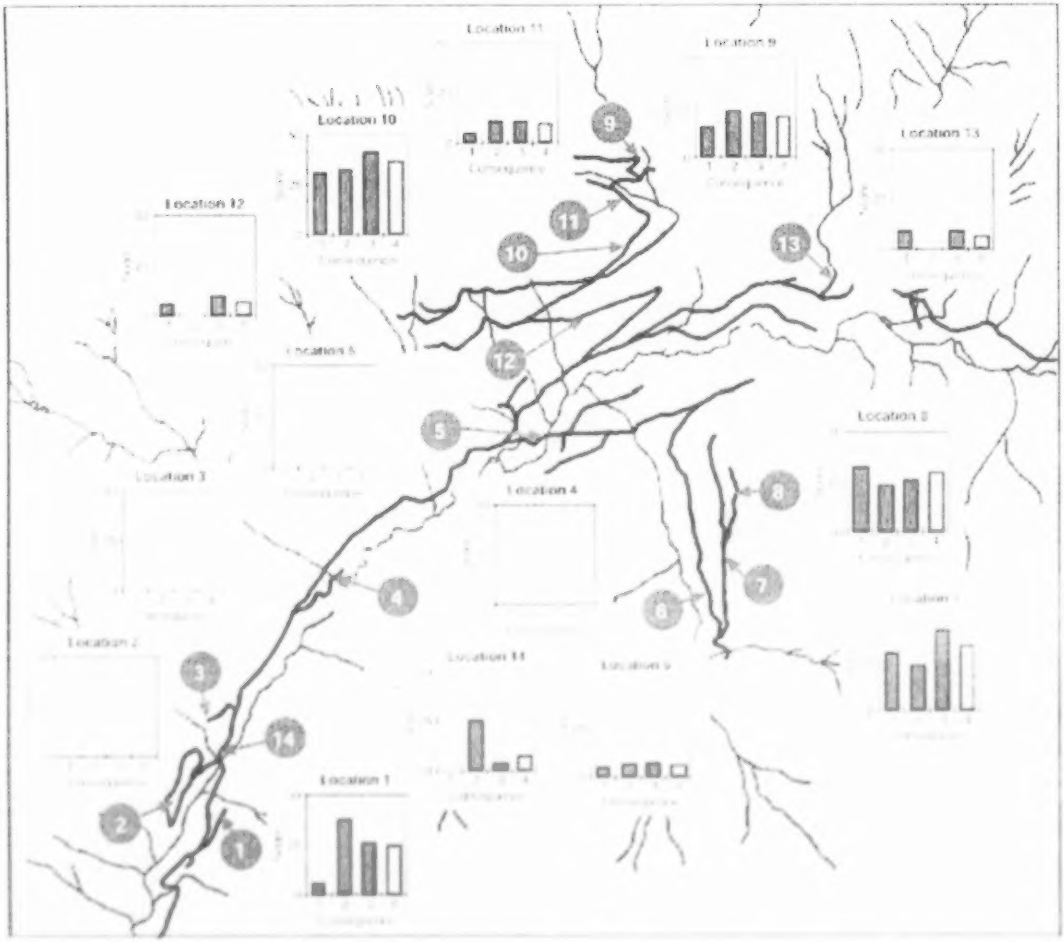
Location 11
Location 9
Location 10
Location 12
Location 13
Location 5
Location 3
Location 8
Location 4
Location 7
Location 2
Location 14
Location 6
Location 1
Consequence
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Figure 4. Displaying the Results – The spreadsheet generates mini-graphs that spatially show the Risk to Humans, Fish and Forest for each location. (Rogers Creek – Squamish Forest District.)

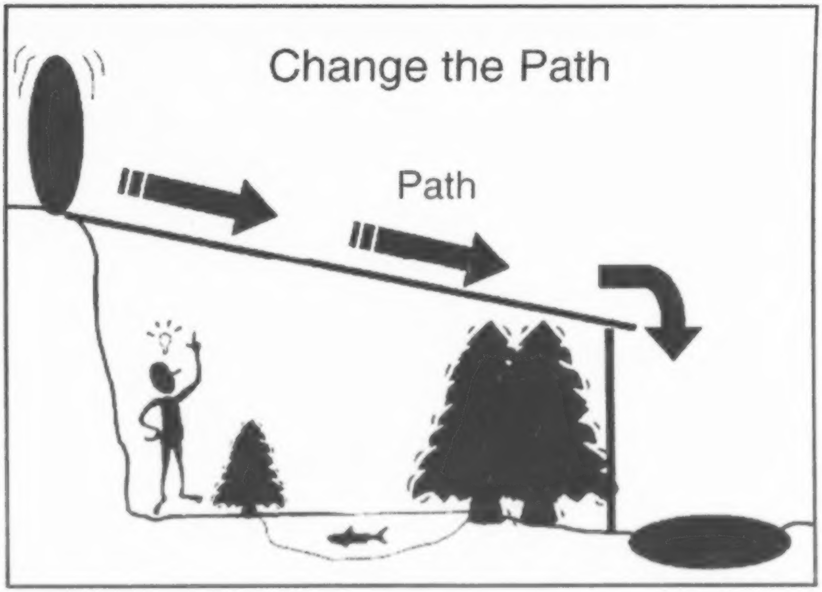
Change the Path
Path

Figure 5. Risk Management – Risk can be lowered to a tolerable level by diverting the event away from components that it could harm.

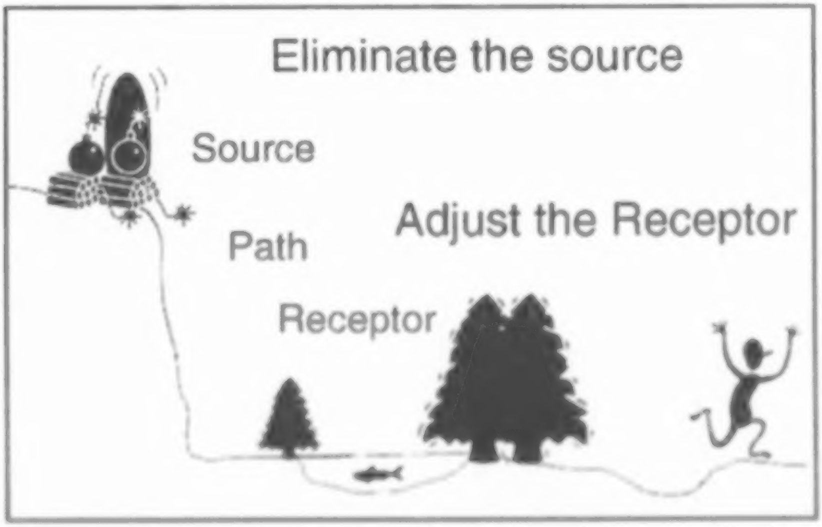
Eliminate the source
Source
Path
Adjust the Receptor
Receptor

Figure 6. Risk Management – The Risk can also be lowered to an acceptable level by destroying the source or by removing the receptor from harm's way.

LANDSLIDE SUSCEPTIBILITY FROM WATERSHED AND FAN CHARACTERISTICS, SALMON ARM AND VERNON FOREST DISTRICTS

Axel Eichd[1] and Ted Fuller[2]

Abstract

Landslide occurrence in the Salmon Arm and Vernon forest districts in the last five years has stimulated research to determine how small drainage basins might be classified into debris flow prone, debris flood prone, or flood prone. Aluvial fans situated at the base of several entrenched stream systems may have people dwelling on them. In addition to safety concerns, water quality and habitat are also of importance. A procedure is presented here that uses both map-based (GIS) and field-based (fan and channel mapping) analysis to show relative risk of impact on fans. Bedrock and surficial geology are used to type the basins that are dominated by metamorphic rocks. Basin area, aspect, slope, inner gorge,and gentle-over-steep conditions were determined. GIS-generated channel longitudinal profiles were compared between the data sets. Fan morphology and stratigraphy aided in identifying previous debris flow events and their magnitude. Historical information provided by time-series air photo interpretation, historic maps, and archival research provides clues to recurence intervals. Some fans will have relict paraglacial deposits that include debris flow and may still support future debris flows. Last, the methods proposed here can be used to signal special concerns for forest development. The use of this template may find application in risk asessment outside the selected forest districts.

Introduction

The purpose of this paper is to develop a landslide susceptibility model. This project, which is in progress, will help determine susceptibility based on watershed and fan characteristics for Hunters Range. It is organized by impetus behind the project, overview of the geographic area, data sources available, and information techology that can be employed. The methods and procedures used will be briefly described, folowed by a summary of the results where the technique was applied in the Salmon Arm and Vernon forest districts.

The concerns in forest development in mourainous terrain in the southern Interior of British Columbia include the occurrence of landslids and debris flows. People living on alluvial fans below harvested watersheds are particularly at risk. Alluvial fans are often the depositional zones of rapid mass movements down steep waterourses. This is a concern due to their sudden and unpredictable occurrence. Forest developmet has sometimes been implicated in the initiation of some of the debris flows in the B.C. Interior

The study was stimulated by our interest in landslides and process geomorphology. We had researched other publications on this topic and wished to try existing methods and new methods

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[1] University of Cologne

[2] B.C. Ministry of Water, Land and Air Protection, 159 Dalhousie Dr., Kamloops, B.C. V2C 5Z5, e-mail: ted.fuller@gems5.gov.bc.ca

on a particular part of the landscape. We decided on the Salmon Arm Forest District and the Vernon Forest District, in particular, the Hunters Range (Figure 1). A total of 56 watersheds were analyzed. The area covered by the Hunters Range is about 1300 km^2 with main drainages of Kingfisher and Yard creeks. It is bounded on the south by Shuswap River, on the north by Eagle River, on the west by Mara Lake, and on the east by Wap Creek and Mabel Lake. One of the largest reported non-volcanic debris flows in British Columbia occurs in this area on Hummingbird Creek (Jakob et al. 2000).

Debris flows result from the interaction of several factors. To create a hazard classification system, an understanding of how each factor contributes to debris flow occurrence is needed. However, key factors including basin morphology, slope, soil moisture, road location, and soil porosity/permeability can be analyzed. Research is needed in (1) identification of fans that are susceptible to debris flow, (2) methods for estimating physical properties and character of debris flows, and (3) characteristics of debris flow source areas (Hungr et al. 1987; Reneau and Dietrich 1987; Ritter et al. 1995). Here, we wish to address the question of what factors trigger debris flows at Hunters Range and what is their relative significance.

Debris flows are gravity-induced rapid mass movements of sediment of varying size ranges, from clay to boulders (Ritter et al. 1995). The transported mass includes varying amounts of water and moves by differential shearing with waves that overtake one another (Johnson and Rahn 1970; Jackson et al. 1987).

It is generally felt that small basins with steep slopes are prone to landslides. This is borne out by the work of Jackson (1987) in the Canadian Rocky Mountains and the Mackenzie Mountains. The ultimate factors that cause debris flows are gravity and water.

Soil porosity and its influence on landslides were investigated by Iverson et al. (2000). In a scale model experiment, they determined that loose soil started sliding about 300 times faster than dense soil. Initial soil porosity of 0.5 led to abrupt failure while that around 0.41 led to slow episodic motion. Critical porosity was 0.44 for landslides. The critical pore water pressure in less dense soils does not have to be as high to trigger a failure.

Data Sources

For at least part of Hunters Range, there exist topographic maps, historical maps, bedrock geology maps, soil maps, and surficial geology that are available to the public. In addition, the provincial government has Terrain Resource Inventory Mapping (TRIM) at 1:20 000 scale with 20 m contour intervals. Their geographic information system (GIS) includes an extension to ArcView 3.1 called Geographic Object Analysis Tool (GOAT). The GIS files include several coverages that assist our tasks, including 1997 black and white orthophoto imagery, slope, road networks, regional bedrock geology, and landslide inventory coverages.

Historic mapping exists for the Railway Belt Surveys, which were carried out along the Canadian Pacific Railway corridor between 1877 and 1907. These show the location of channels traversing fans in the valley of the Shuswap River, for example (Figure 2). Geological Survey of

Canada surficial geology maps show fans, alluvium, moraine, and lacustrine deposits for part of the area (Fulton 1975). Terrain mapping has been done over part of the Hunters Range (EBA Engineering 1998). The soil coverage was based on Kowall (1980).

Archival material was searched out and collected from various newspapers (Kamloops Sentinel, Enderby Commoner) and the Enderby Museum.

Because water is a key component for debris flow systems, its spatial concentration should be included in this model. This would include the sources of water (snowmelt, rainfall, rain-on-snow) as well as the routes that surface runoff takes once on the ground. Drainage networks are mapped to varying degrees but road systems can also redirect water, intercept shallow groundwater and vadose zone water, and expand the volume flowing across the surface.

Precipitation data are only available from a few sites (Salmon Arm stations and Ministry of Forests Sicamous Research Site stations). Gauged streams in Hunters Range are rare but there exist some spotty records. The PRISM model (**P**arameter-elevation **R**egressions on **I**ndependent **S**lopes **M**odel) developed at Oregon State University was used by Ministry of Forests to develop a 4 km by 4 km grid of mean annual precipitation.[3] These data were provided to us from Ministry of Forests.

Tools

ESRI ArcInfo and ESRI ArcView as well as Microsoft Excel were used as analysis tools. Digitizing was done at Ministry of Environment, Lands and Parks and University College of the Cariboo. GIS is a powerful tool that can enhance the establishment of a hazard classification system. However, it is a tool only and the user must be able to incorporate it correctly into the process.

The overlay analysis is based on the combination of layers. Each layer represents one specific factor, such as aspect or soil type, and divides the study area into polygons according to the values of its factor. By combining layers, a new layer is generated. The polygons of this newly generated layer contain one, and only one, attribute value of the layers it derived from. For instance, the combination of an aspect layer with a soil layer would generate a new layer that would divide the area into polygons in a way that each polygon contained exactly one aspect value and exactly one soil type value. Each polygon contains information about all factors at its specific location.

Based on this overlay analysis, two main approaches are used to implement a GIS into the establishment of a hazard classification scheme: the process-based approach and the stochastic approach. In the following sections, both methods are examined.

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[3] http://www.ocs.orst.edu/prism/gcm_toc.html

Process-Based Approach

The processed-based approach is concerned with the physical processes involved in debris flows and takes geotechnical parameters, such as cohesion or angle of internal friction, into consideration. Its main focus lies on the determination of the safety factor. Sakellariou and Ferentinou (2001) employed a process-based approach in a study that treats of the estimation of slope stability. To begin with, a digital elevation model (DEM) was created that provided information about geomorphic factors such as slope angle, aspect, and elevation. A second layer was then created in which geotechnical data, such as cohesion, angle of internal friction, thickness of layers, or depth of groundwater, were stored. These data, before being evaluated, had to be transformed in a way that corresponded to the homogeneity of data structure, which is required for process-based models. For this reason, average values were used. The two layers were overlaid so that the newly generated layer contained information about both the geomorphic and geotechnical data for each polygon. The next step was the implementation of a "Landslide Hazard Assessment Tool." This tool automatically calculated the safety factory for each polygon. The calculation was based on the following equation:

$$F = 2.27 \cdot \frac{c \operatorname{cosec} \psi_f}{\gamma H} + 1.54 \cdot (1 - r_u) \cdot \cot \psi_f \cdot \tan \varphi$$

The parameters involved in this equation are F = safety factor, γ = unit weight of soil, c = cohesion, φ = internal friction angle, ψ_f = slope angle, H = slope height, and r_u = pore water pressure ratio. The equation was proposed by Sah et al. (1994) in Sakellariou and Ferentinou (2001).

According to the values of these parameters, the program calculates a safety factor for each polygon. The spatial distribution of this safety factor can be visualized in a map identifying the risk of slope failure for every polygon. The user of this "Landslide Hazard Assessment Tool" can change the values of the parameters easily and, by doing so, create a set of maps representing different scenarios. These maps can be compared with a map representing real locations of slope failure. The combination of values that makes the best match can be determined.

The advantage of such a process-based method is that it is physically based. It is possible to identify a fine-scale pattern of instability. However, it can be difficult to acquire the input data necessary to use this method effectively. Geotechnical parameters often have to be measured in the field, which is time and cost consuming.

Therefore, the process-based method is well suited for the analysis of smaller areas (Linebuck Gritzner et al. 2000). The study conducted by Sakellariou and Ferentinou (2001), for example, covered an area of 48 km^2.

Stochastic Approach

The stochastic approach is another way of implementing a GIS into the establishment of a hazard classification scheme. This method is based on the assumption that the conditions that triggered slope failures in the past are likely to cause future slope failures. In the stochastic approach used by Dhakal et al. (2000), the focus is not on the safety factor and the required geotechnical data, but on geomorphic, geologic, climatic, and vegetation factors, which are considered to be indices of the parameters of the safety factor. These factors are analyzed, generally employing multivariate statistical analysis techniques. As the stochastic approach is going to be employed for the project at Hunters Range, the study conducted by Dhakal et al. (2000) will be examined in detail.

The database for the study was built by taking the following steps. First, landslide locations were identified on 1:20 000 air photographs and plotted on a 1:12 500 topographic hardcopy map. This landslide distribution map was digitized. Next, a DEM was generated providing information about slope gradient, elevation, and aspect. To classify these data, the slope gradient was divided into five classes: < 15°, 15–25°, 25–35°, 35–45°, and > 45°. The elevation was divided into four classes: < 1800 m, 1800–2000 m, 2000–2200 m, and > 2200 m. The aspect was also divided into four classes: north (315–45°), east (45–135°), south (135–225°), west (225–315°). Moreover, ridges and valleys were identified from the DEM. Six classes were created based on the distance to these features. The next step involved the generation of (1) a land use/land-cover layer, which derived from a 1:25 000 land use/land-cover map; (2) a geology layer, which derived from a 1:50 000 geology map; and (3) a basin order layer (first, second, third order), which derived from a topographic map. Land use/land-cover data were divided into five classes, geology data into seven classes, and basin order into three classes. These layers will be referred to as factor layers.

The analysis of the database was based on a Q-S II analysis.[4] This combines a multidimensional quantification analysis and the equivalent of a discriminant analysis. The difference, however, is that this function incorporates nominal data instead of interval or ratio data. Nominal scaled factors, such as geology or land use/land-cover, are often crucial to discriminate between landslide and non-landslide groups. A discriminant analysis can be employed to determine whether the variables used are able to explain spatial differences, such as "landslide" or "non-landslide." In addition, it can provide information to what extent each variable contributes to the spatial differentiation (Bahrenberg et al. 1992). For the purpose of determining a spatial differentiation, Dhakal et al. (2000) created a landslide group and a non-landslide group. The first question to be answered was which sampling method for the non-landslide group would provide more discriminant and thus meaningful results. The two methods in question were the aligned systematic sampling method and the unaligned stratified random sampling method. As only the results themselves could give an answer, the analysis was conducted for both sampling methods and their results were compared afterwards. This means that two samples were created using the aligned systematic method, and three samples were created using the unaligned stratified random method. The Q-S II analysis was made in the Japanese version of the SPSS[5] statistical package and used the attribute tables of the previously created factor layers.

The analysis started with the calculation of the correlation coefficients between the factors, which from now on will be referred to as variables. The aim was to see if any two variables vary in a similar way. For example, if the values of elevation and slope angle are highly correlated, then one of these two variables could be excluded from the analysis. In the case of the study conducted by Dhakal et al. (2000), however, no strong correlations appeared, which simply indicates that all eight variables contribute to the occurrence of landslides in their own specific way and therefore should be integrated in the Q-S II analysis.

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[4] Q-S II is a statistical analysis of quantification scaling type II used in a GIS application.

[5] SPSS Inc. is Statistical Package for the Social Sciences software system.

The Q-S II analysis was supposed to provide information about (1) which sampling method leads to more discriminant results and (2) to what extent each variable contributes to the occurrence of landslides. To determine the efficiency of the discrimination between the two groups, the correlation ratio, η^2, and eta, η, were calculated. The correlation ratio is referred to as the "...proportion of variance between the groups to the total variance...." and eta is referred to as "...the degree of difference between the group means." (Dhakal et al. 2000). Higher η^2 and η scores indicate a more efficient discrimination. Analysis results show that the unaligned stratified random sampling method led to a more efficient discrimination between the two groups, thus providing more meaningful results. The second aim of the Q-S II analysis was to determine the importance of each variable. For this purpose, the scores of all classes of all variables were compared. According to the Q-S II functions, a larger class score (CS) indicates a greater contribution of this class to landslides. In addition, the range of scores (RS) within every class was calculated and compared. As to the class scores themselves, a larger range of scores indicates a greater contribution of this variable to landslides. Hence, the analysis did not only determine the importance of each variable (RS), but moreover provided information about the importance of each class of every variable, too.

The stochastic approach made it apparent that geology is the most contributing variable (RS = 2.557) and that the class "granite" of this variable is the one most inclined to landslides (CS = –0.708). Geology is followed by elevation (RS = 0.835) with the highest class score for "2000–2200 m" (CS = –0.412). Other important variables are slope aspect (RS = 0.831) with the highest class score for "south" (CS = –0.358) and land use/land-cover (RS = 0.769) with the highest class score for "shrub land" (CS = –0.443). The analysis showed that the variables distance from ridge, distance from valley, and slope gradient only have a minor impact on the occurrence of landslides. Their range of scores is 0.081, 0.145, and 0.268, respectively. Their largest class score is –0.033, –0.097, and –0.194, respectively.

The next step of the study focused on the determination of hazard classes. Each previously generated factor resulting from the Q-S II analysis layer now contained data about the scores for its classes. The factor layers were overlaid so that one layer was generated, which contained a cumulative score for each polygon. Cumulative scores of the landslide group were compared with cumulative scores of the non-landslide group. A discriminant score was determined that divided the polygons into "stable" and "unstable" according to their cumulative score. In this study, the discriminant score was –0.13. A further differentiation between very unstable and marginally unstable, as well as very stable and marginally stable, respectively, was made. This differentiation was based on the accuracy of decision, meaning that the top 20% of each group were identified as being very unstable and very stable, respectively. These four categories were considered to be four classes of relative hazard: high, moderate, less, least. Landslide hazard maps were produced taking the ranked cumulative score of each polygon into account as the foundation.

The last step of the study involved the evaluation of these hazard maps. The method employed was to calculate the percentage of landslides for each hazard class by overlaying the landslide hazard map with the previously created layer representing real landslide locations. A high percentage of landslides in polygons, which had been ranked as high hazard, indicated a high accuracy of the hazard map. To determine to what extent the five different samples led to different results, two of the five hazard maps were overlaid in turn. Those polygons that had the same hazard class were counted. The proportion of these polygons to the total number of polygons was considered to be the "overall spatial agreement." It became apparent that differences were minor between samples resulting from the same sampling method. Dhakal et al. (2000) inferred that one sample set would satisfy the analysis and hazard mapping requirements if the unaligned stratified random sampling method was employed.

Dhakal et al. (2000) employed a stochastic approach using the capabilities of a GIS in combination with the analysis capabilities of the statistic program SPSS. This method is appropriate especially for large areas. The study conducted by Dhakal et al. (2000) covered an area of 124 km^2. In light of the often difficult, if not impossible, data acquisition that comes along with process-based methods, the benefits of a stochastic approach are that it can be made rapidly and that site investigation costs are minimized. Moreover, the incorporation of a GIS has further enhanced this method (Dhakal et al. 2000).

Two aspects must be emphasized however. First, the validity of any statistical or GIS-based approach largely depends on how complete and accurate the input data are. For this reason, it is mandatory that the analysis be strictly based on variables for which appropriate data are available. Incomplete or inaccurate data can easily lead to invalid results. Second, although certain statistical analysis functions are part of every GIS, a sophisticated statistical analysis can be better undertaken employing a statistic program. It is important that the user of a GIS analysis understands which steps of a project can be conducted efficiently by using a GIS and which steps can be better carried out by employing other tools. This means that often a GIS is a powerful tool to establish a comprehensive database (overlay function) and a powerful tool to visualize and evaluate gained results (hazard maps). On the other hand, a statistics program can often carry out the analysis of the database more effectively.

From these tools, watershed characteristics were derived. These included watershed area, perimeter, basin relief, maximum and minimum elevation, fan area, fan slope, aspect, slope classes, and Melton's ruggedness, for each sub-basin. Melton's ruggedness (MR) is defined as:

$$\text{Ruggedness} = \text{Height of Basin} \times (\text{Area of Basin})^{-0.5}$$

$$MR = Hb(Ab)^{-0.5}$$

Melton's ruggedness provides a unitless number to compare basins. It has been used in the Canadian Rocky Mountains to help differentiate debris flow impacted fans from alluvial fans (Jackson 1987). Melton's ruggedness was also used in a study conducted by EBA Engineering (1999) following suggestions from Ted Fuller. This study provided an inventory of high consequence terrain in the Salmon Arm Forest District. An example to test this is from Camp Creek, the site of a 1968 debris flow in the Eagle River valley north of Hunters Range. The parameters used are $Hb = 1660$ m and $Ab = 15$ km^2 = 15 000m^2, which give a Melton's ruggedness number of 0.429.

Graphical Methods

Basin area was plotted against basin relief for the watersheds as a log-linear plot (Figure 3). Melton's ruggedness number was plotted against slope of the fan (also logarithmic scales) (Figure 4). In this way, known fan impacts can be shown with their relationship to a few basin parameters. Speculations from these graphs suggest that large basins with lower relief are fluvial fan derived while smaller basins with high relief are debris flow fan derived. A suggestive curve is drawn through these data with debris flow above the curve and non-debris flow below. In addition, watershed area was plotted against fan area (Figure 5) and shows a wide scatter in the data.

Watershed slope distributions were determined from a digital elevation model (DEM) for selected watersheds. The slope classification was divided into 17 classes. The first class was 0–2%, the second 2–5%, the third 5–10%, and then in increments of 10%. Histograms were plotted to show slope distributions (Figures 6 and 7). Analysis of the slope data is in progress.

Debris Flow Runout

Debris flow runout is an important physical attribute to obtain and inventory. At present, there is limited information on debris flow runout in the Hunters Range. The runout of coarse rubbly size material or fine muddy matrix material will be different. In this study, the runout was determined from 1997 four (4) m pixel resolution orthophoto imagery by examining the extent of the debris flow path. By using examples from Hummingbird Creek, Fall Creek, Rogers Creek, Hunter Creek from Hunters Range, as well as Leonard Creek, Eagle Valley creeks near Malakwa, and Falkland Creek, generalities can be made. Typical debris flows are transported in channel gradients of 16° and higher and run out on fan slopes of 3° or higher. Large debris flows extend onto fans less than 3° such as the case of the Hummingbird Creek fan.

Conclusions

The aim of this paper is to create a platform for the project "Establishment of a GIS-based Hazard Classification Scheme for Debris Flows, Hunters Range, British Columbia." For this purpose, the current status of research regarding debris flows and landslides was investigated. This investigation demonstrated that debris flow initiation is the result of basin morphometry, slope gradient, soil moisture, and roads.

Small and steep basins are highly vulnerable to debris flows. Determining Melton's ruggedness number is a method for summarizing the interrelation of morphometric basin parameters. Slope gradients can be classified with respect to debris flow occurrence. It appears that there is a relatively higher concentration of debris flows on slopes with a gradient of approximately 30° or more. Furthermore, soil moisture significantly contributes to the initiation of debris flows. Increased soil moisture conditions can be the result of either severe storms or road construction.

Road construction affects the water regime of a basin in two ways: (1) relatively permanent gaps in the forest canopy lead to increased water storage in the soil and snowpack, and (2) the water routing to streams is spatially concentrated. The behaviour of landslides is strongly connected to initial soil porosity. Landslides initiated in loose soil show a sudden and fast motion, whereas the motion of landslides initiated in dense soil is dilative, episodic, and slow. In addition, the critical pore water pressure of dense soil is roughly twice as large as the one of loose soil.

Although engineers and geoscientists have been able to uncover many of the mechanisms of how single factors contribute to the occurrence of debris flows, there still remain unanswered questions. The major problem is the interaction of these factors, which is only poorly understood. This is the reason why prediction of debris flows is difficult.

In addition to the investigation of the factors causing debris flows, this paper examined two different approaches are used to implement a GIS into the establishment of a hazard classification scheme. The process-based approach seems to be a useful method for the analysis of small areas, as geotechnical data acquisition is time and cost consuming. The results gained this way, though, provide a high degree of precision (but not necessarily accuracy if modelled incorrectly). The stochastic approach, on the other hand, appears to be well suited for the investigation of larger areas, as geotechnical data are not required.

The debris flow phenomenon is the result of the complex interplay between various factors. Sophisticated methods for a reliable prediction of debris flows have not been able to be developed yet. Due to the progress in the field of GIS technology in the past two decades, this technology is bound to play a key role in the enhancement of methods for the prediction of debris flows.

GIS is a useful tool for calculating Melton's ruggedness, basin characteristics (slope, aspect), stream gradients, and long profiles of streams. However, GIS should not be the only method used for this type of investigation.

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References

Aronoff, S. 1995. Geographic information systems: A management perspective. WDL Publications. Ottawa.

Bahrenberg, G., E. Giese, and J. Nipper. 1992. Statistische Methoden in der Geographie 2. Stuttgart, B.G. Teubner, Studienbuecher der Geographie.

Dhakal, A.S., T. Amada, and M. Aniya. 2000. Landslide hazard mapping and its evaluation using GIS: An investigation of sampling schemes for a grid-cell based quantitative method. Photogrammetric Eng. Remote Sensing 66(8):981–989.

EBA Engineering Consultants Ltd. 1998. Terrain mapping level C, Hunters Range. Prepared for Riverside Forest Products Ltd.

EBA Engineering Consultants Ltd. 1999. Inventory of high consequence terrain, Salmon Arm Forest District. Vancouver, B.C. Project No. 0801-99-81022.

Fulton, R.J. 1975. Quaternary geology and geomorphology, Nicola-Vernon area, British Columbia. Geol. Surv. Can. Mem. 380. 50 p.

Hungr, O., Morgan, G.C., Vandine, D.F. and D.R Lister. 1987. Debris flow defenses in British Columbia. In Debris Flows/Avalanches: Process, Recognition, and Mitigation. p. 201-222. Ed. By J.E. Costa and G.F. Wieczorek, Boulder, Geological Society of America, Reviews in Engineering Geology, 7.

Iverson, R.M., M.E. Reid, N.R. Iverson, R.G. LaHusen, M. Logan, J.E. Mann, and D.L. Brien. 2000. Acute sensitivity of landslide rates to initial soil porosity. Science 290:20.

Jackson, L.E., Jr. 1987. Debris flow hazard in the Canadian Rocky Mountains. Geol. Surv. Can. 86-11. 20 p.

Jackson, L.E., Jr., R.A. Kostaschuk, and G.M. MacDonald. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. *In* Proc. Debris Flows/Avalanches: Process, Recognition and Mitigation. J.E. Costa and G.F. Wieczorek (editors). Reno, Nev. Rev. Eng. Geol. 7, Geol. Soc. Am., Boulder, Colo., pp. 115–124.

Jakob, M., D. Anderson, T. Fuller, O. Hunger, and D. Ayotte. 2000. An unusually large debris flow at Hummingbird Creek, Mara Lake, British Columbia. Can. Geotech. J. 37:1109–1125.

Johnson, A.M. and P.H. Rahn. 1970. Mobilization of debris flows. In New Contributions to Slope Evolution, Zeitschrift fuer Geomorphologie, Suppl. 9, p. 168-186.

Kowall, R.C. 1980. Soils and terrain of the Seymour Arm area. B.C. Min. Environ., Resour. Analysis Br., Victoria, B.C. B.C. Soil Survey Rep. No. 16.

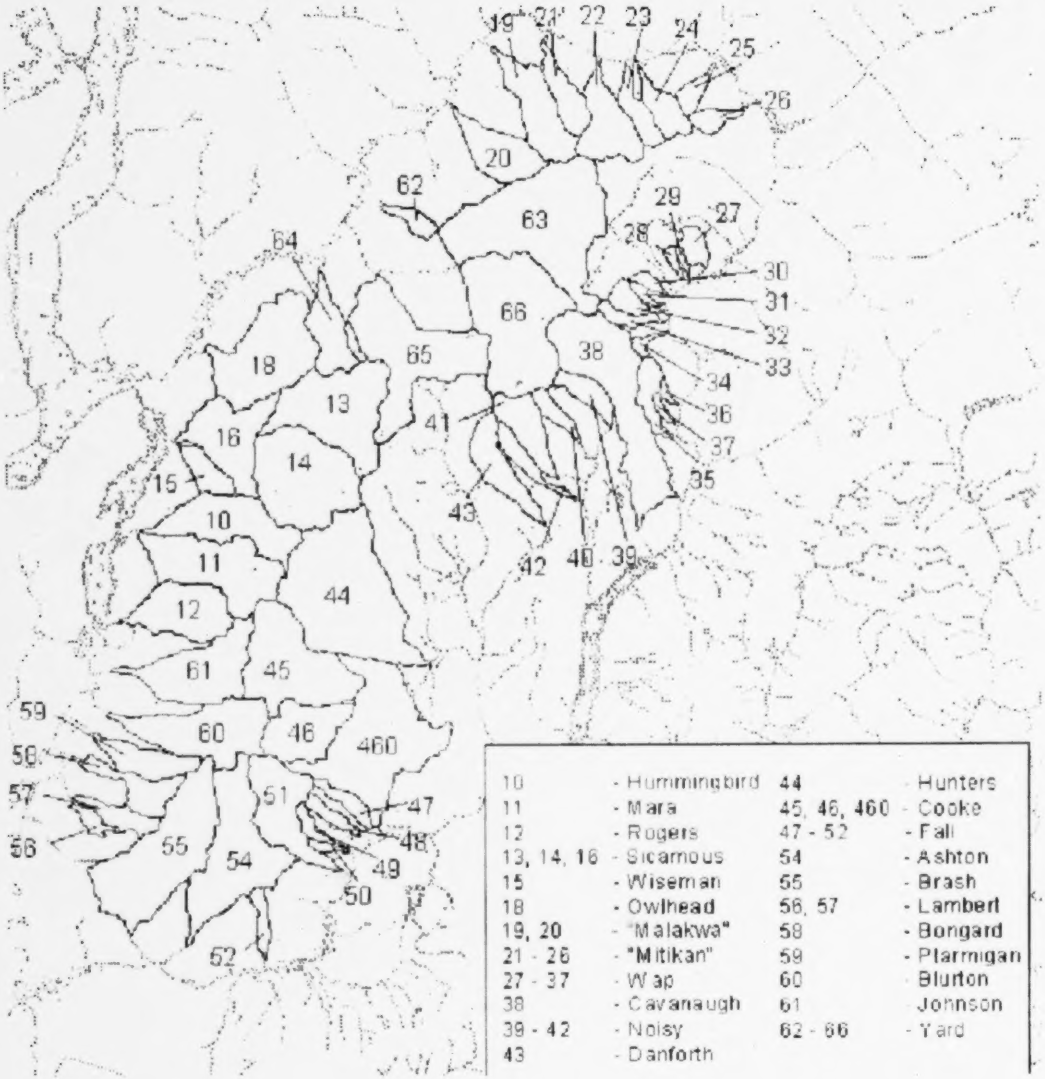
Lineback Gritzner, M., W. Andrew Marcus, R. Aspinall, and S.G. Custer. 2000. Assessing landslide potential using GIS, soil wetness modeling and topographic attributes, Payette River, Idaho. Geomorphology 37:149–165.

Reneau, S.L. and W.E. Dietrich. 1987. The importance of hollows in debris flow studies; Examples from Marin County, California. In Debris Flows/ Avalanches: Process, Recognition, and Mitigation, p. 165-180. Ed. By J.E. Costa and G.F. Wieczorek, Boulder, Geological Society of America, Reviews in Engineering Geology, 7.

Ritter, D.F., R.C. Kochel, and J.R. Miller. 1995. Process geomorphology. 3rd ed. WBC Publishers. Toronto.

Sah, N.K., Sheorey, P.R. and L.N. Upadhyana. 1994, *Maximum likelihood estimation of slope stability*, Int. Journal of Rock Mech. Min. Sci. & Geomech. Abstract., Oxford, U.K., 31(1), 47 – 53.

Sakellariou, M.G. and M.D. Ferentinou. 2001. GIS-based estimation of slope stability. Nat. Hazards Rev. Feb. 2(1): 12-21.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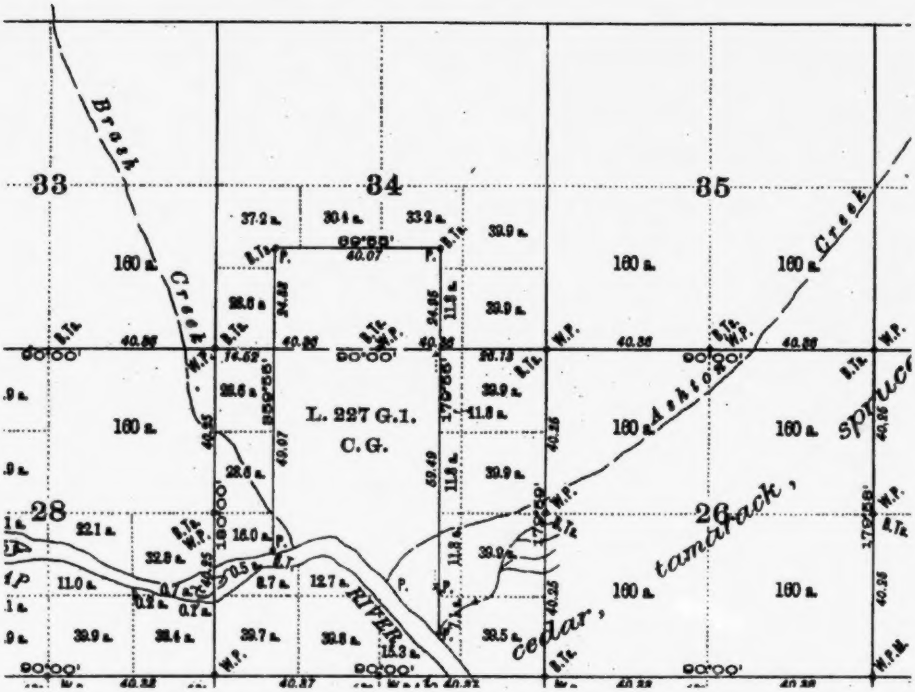
10 - Hummingbird
11 - Mara
12 - Rogers
13, 14, 16 - Sicamous
15 - Wiseman
18 - Owlhead
19, 20 - "Malakwa"
21 - 26 - "Mitikan"
27 - 37 - Wap
38 - Cavanaugh
39 - 42 - Noisy
43 - Danforth
44 - Hunters
45, 46, 460 - Cooke
47 - 52 - Fall
54 - Ashton
55 - Brash
56, 57 - Lambert
58 - Bongard
59 - Ptarmigan
60 - Blurton
61 - Johnson
62 - 66 - Yard

Figure 1. Location of 56 watersheds in Hunters Range.


Brash Creek
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28
26
L. 227 G.1.
C. G.
Ashton Creek
RIVER
cedar, tamarack, spruce
160 a.

Figure 2. Historic Railway Belt map showing Brash Creek and Ashton Creek confluences with Shuswap River.

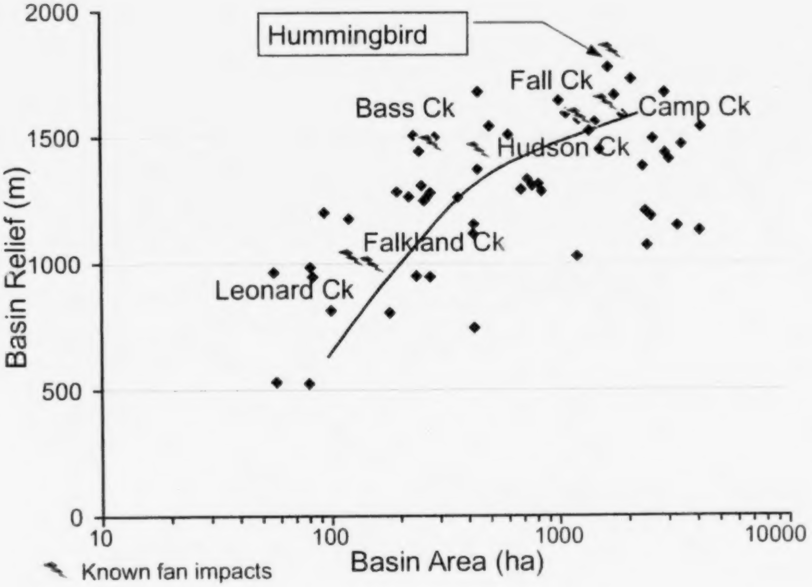


Figure 3. Basin area versus basin relief.

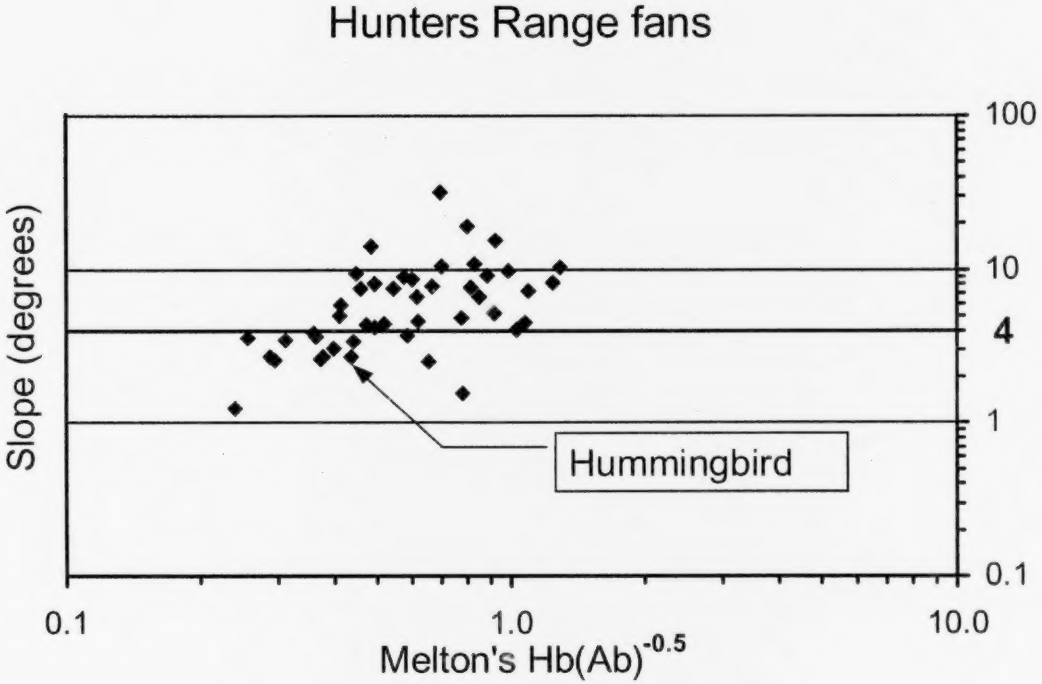


Figure 4. Melton's ruggedness versus fan slope.

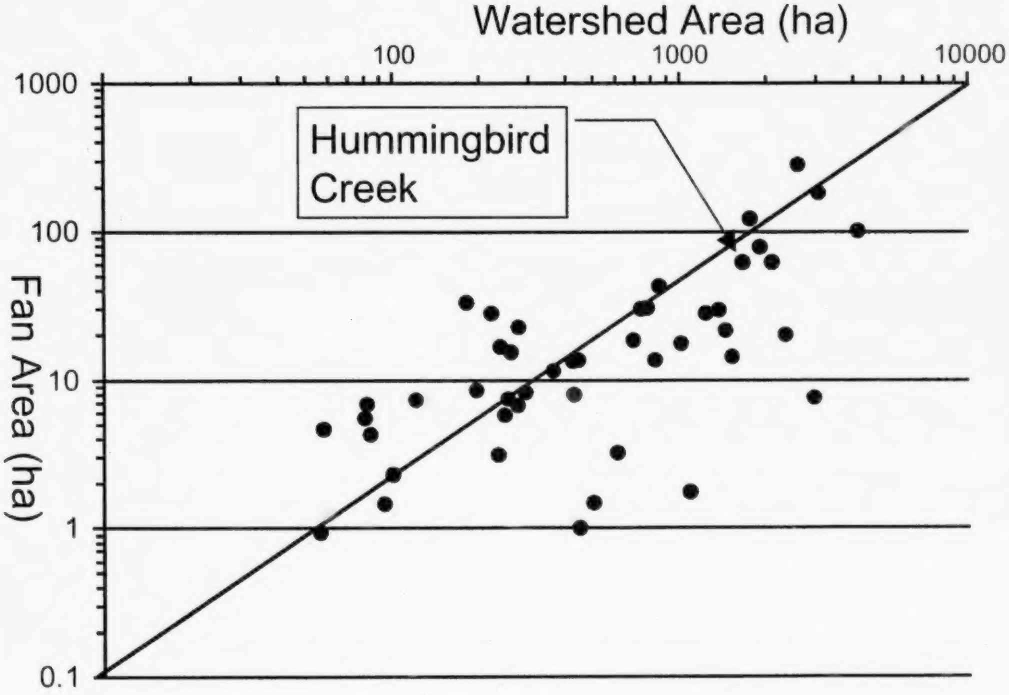


Figure 5. Watershed area versus fan area.

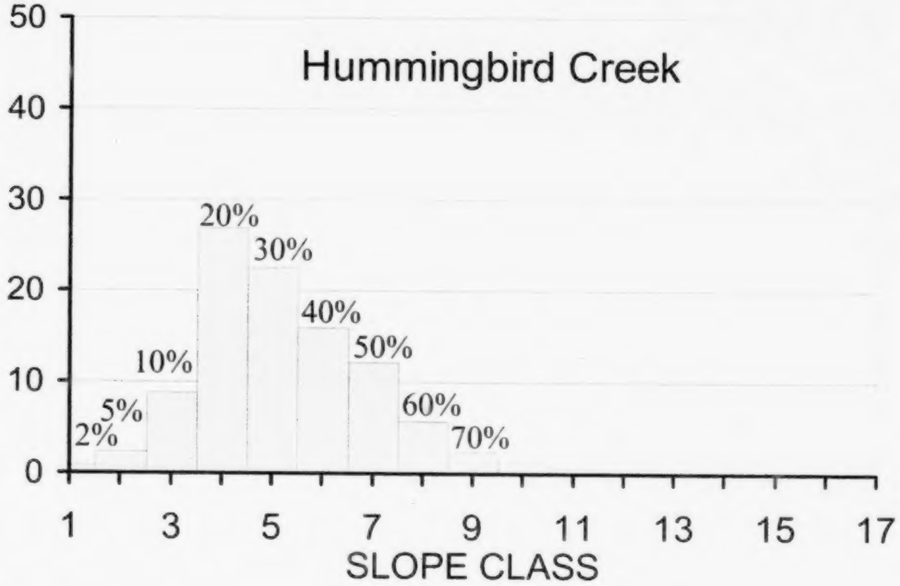


Figure 6. Slope classification for Hummingbird Creek.

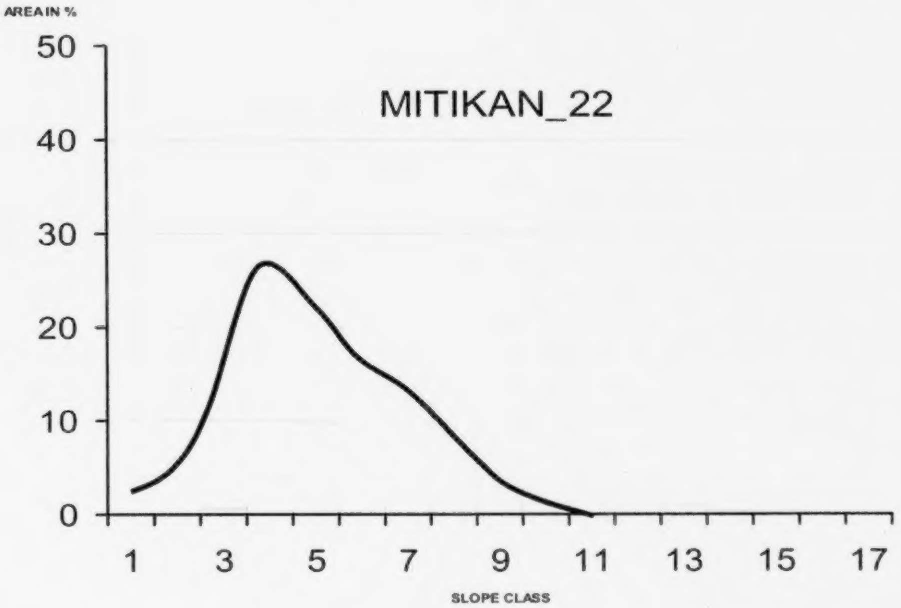


Figure 7. Slope classification of Mitikan_22 watershed with Hummingbird Creek watershed superimposed.

An application of risk analyses in the forest sector using judgmental probability and decision (fault) tree analysis

DOUG NICOL

ABSTRACT

Judgmental probabilities and fault tree analyses have been used to estimate the risk associated with specific forest road segments to downslope resources. An example is reviewed showing its application.

The example arises as a result of 1960's and early 1970's logging practices. Two small creeks located in the northern portion of the Arrow Forest District in southeastern B.C. contained debris from the construction of old trails and roads. Some of this debris/fill is now failing as a result of diverted water and rotting organics. One of the creek channels is within a domestic watershed while the other is located above a residence. Adjacent gullies have experienced road related fill slope failures as a result of the old skid trails/roads. The identified hazards entailed debris slides and debris flows that would potentially mobilize to the valley bottom. A traditional forest sector risk analysis would consist of identifying the hazard qualitatively (hazard simply consisting of likelihood of landslide) multiplied by a qualitative consequence (low, moderate, or high).

For comparison purposes, the risk was estimated using a decision tree (fault tree) analysis through the application of judgmental probabilities. The decision tree analyses provided additional clarity with respect to the level of risk and allowed the resource managers to better evaluate the risk and determine the level of required remedial works.

Risk Analyses in the Forest Sector Using Judgemental Probabilities and Decision Tree Analysis

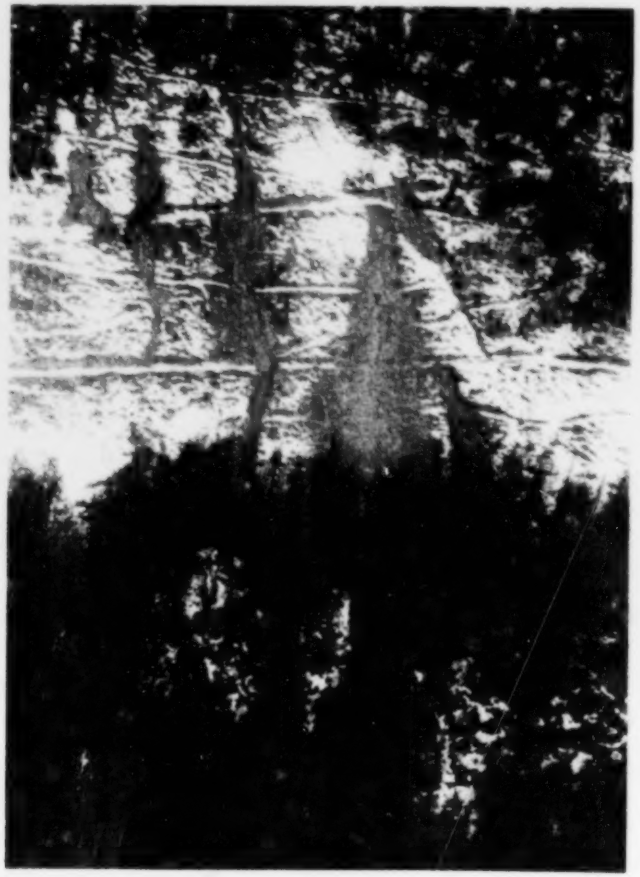
Judgemental Probabilities

Case History Review

- 1960's & 1970's Harvesting
- Gully criss crossed by roads & skid trails.
- Wood supported/steep fills in gully not deactivated
- Residence located near base of gully
- Problem 'discovered' in the fall of 2000.

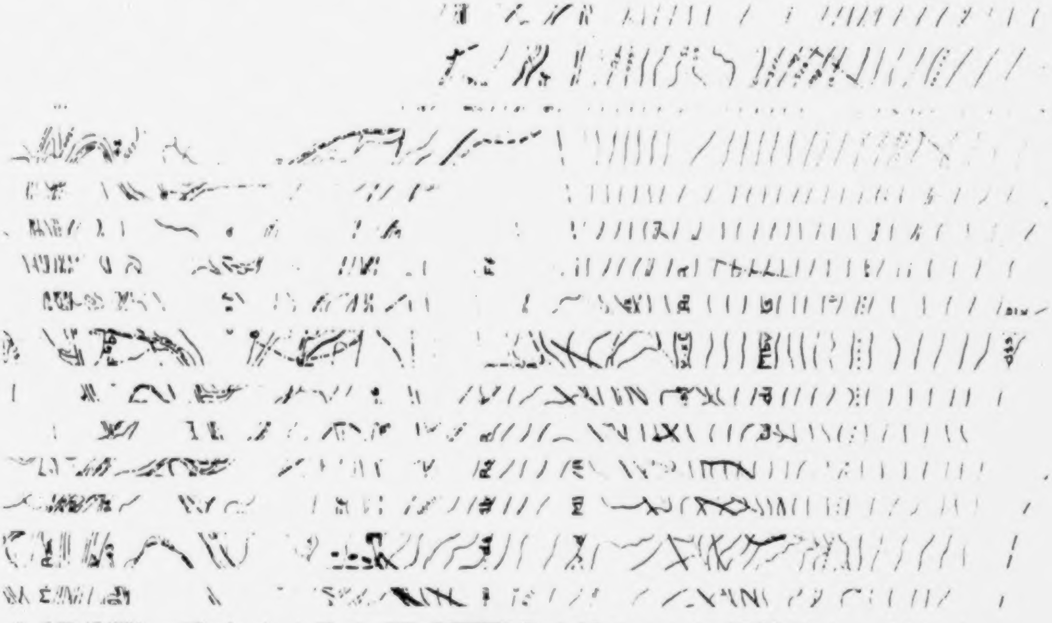
Judgemental Probabilities

- Once the problem was ‘discovered’ and reported on - the site was revisited to determine the relative hazard and potential consequences



Determining the hazard and consequences

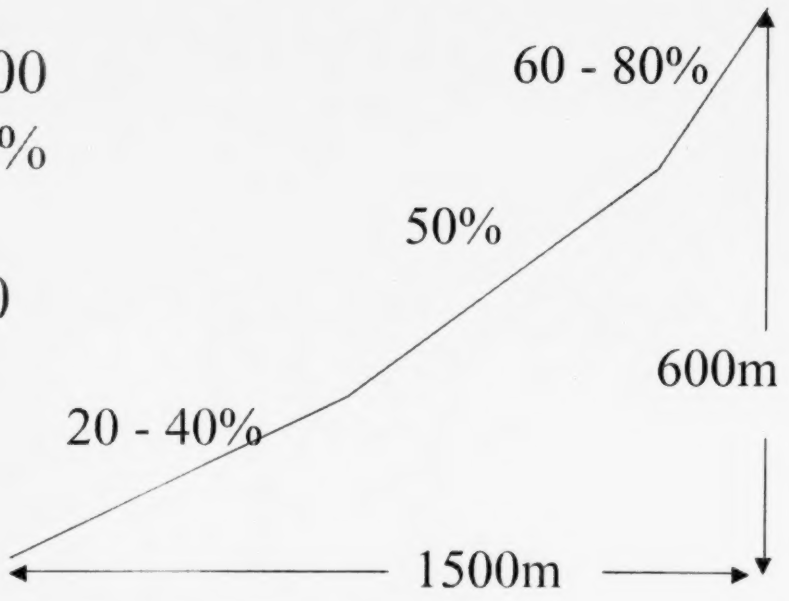
- In late October (2000) the site was revisited
- The entire channel was walked from top to bottom (1130m elevation to 525m elevation)



50
oA
rail
rail p

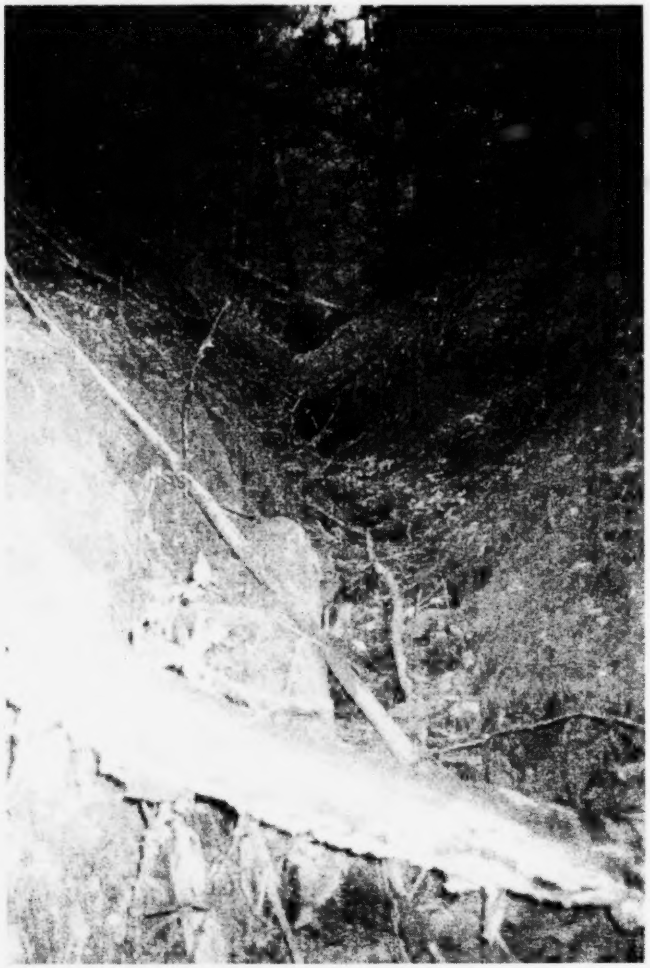
Channel Gradients

- Channel Gradients ranged from 60% to 80% for the upper 200 vertical meters to 50% in the middle 300 vertical meters, to 20 to 40% in the lower 100 vertical meters.


60 - 80%
50%
20 - 40%
600m
1500m

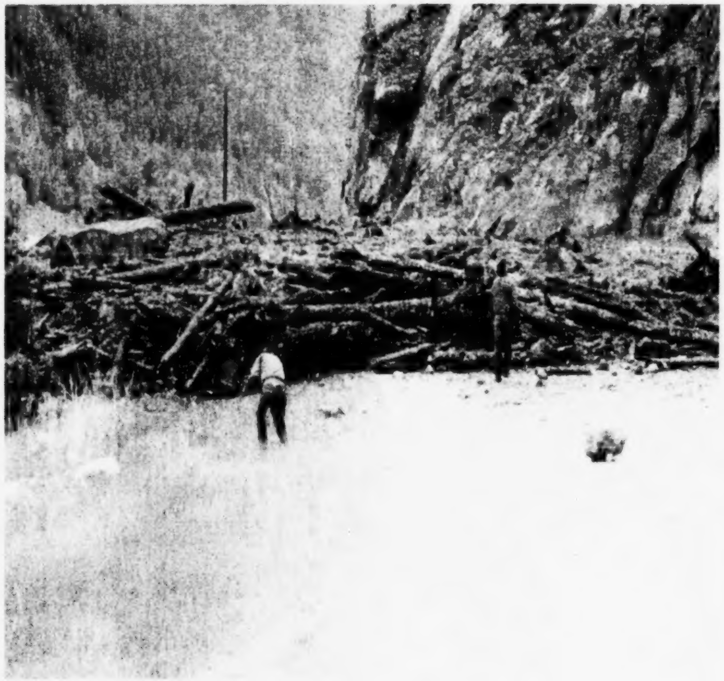
Creek Flows

- From October to November the lower portion of the creek was dry
- Discussions with local residents indicated that the creek flows during the spring but quickly runs dry during early summer.



Channel Assessment

- Debris Jam at 1035m (resulting from natural translational sidewall slides)
- 1025m - debris in gully from skid trail construction and from skid trail failures. Some wood supported fill and diverted drainage.



Channel Assessment

- 975m - Skid trail crossing with wood supported fill - portion has failed down to 935m (1000m3 in debris jam).
- 880m - debris piled against standing timber

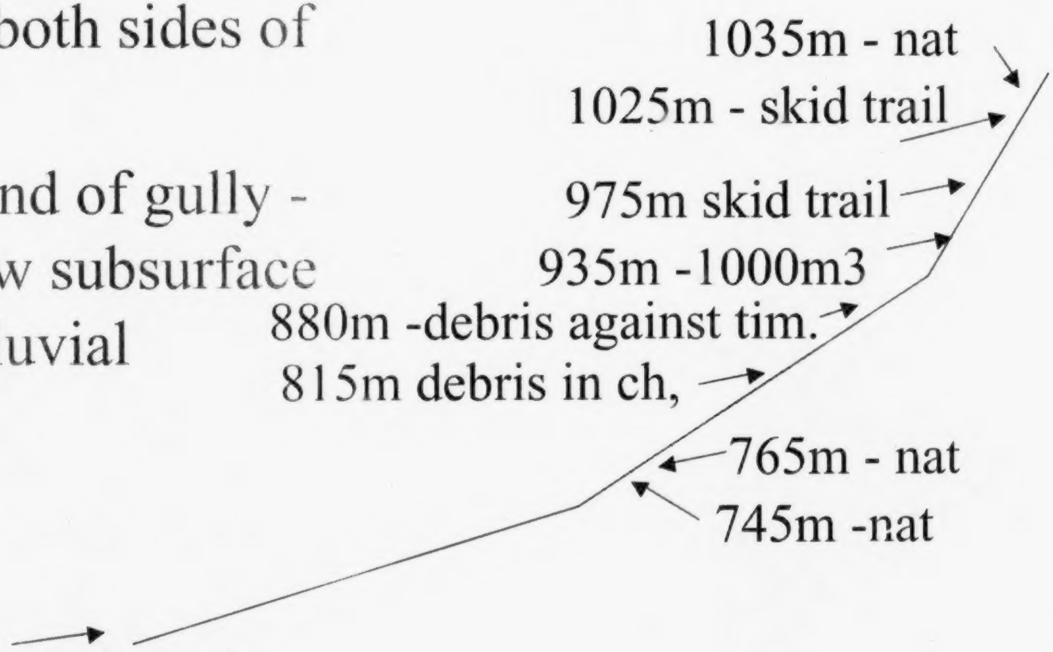
Channel Assessment

- 815m - logs and woody debris piled into channel creating a debris jam
- 765m - debris jam - (natural)
- 745m - debris jam - (natural)

935m

Channel Assessment

- 545m - large debris lobes on both sides of channel
- 525m - End of gully - water flow subsurface - thick alluvial deposits.



1035m - nat

1025m - skid trail

975m skid trail

935m -1000m3

880m -debris against tim.

815m debris in ch,

765m - nat

745m -nat

545m - end of channel

Conventional Forestry Risk Assessment

- Hazard - High
- Consequence - High (it's possible the debris flow will be directed towards the residence)
- Risk - Very High

A SIMPLE QUALITATIVE RISK MATRIX

RISK *What is the likelihood that a landslide will occur **and** cause damage to or loss of a resource?*		**Landslide Consequence** What is the likelihood that debris or sediment will reach the resource, **and** cause damage or loss to the resource, if the landslide occurs?			
		VL	**L**	**M**	**H**
Landslide Hazard What is the likelihood of landslide occurrence as a function of type and size?	**VL**	*Neg*	*VL*	*VL*	*L*
	L	*VL*	*VL*	*L*	*M*
	M	*VL*	*L*	*M*	*H*
	H	*L*	*M*	*H*	*VH*

What to do - Diversion Berm?

- Construct Diversion Berm (near residence). This will result in a high likelihood of a debris flow, low consequence, and moderate risk. Is this satisfactory?

What to do - Pullback and recontour skid trails?

- Results in a moderate to high hazard
- Consequence still high (because of natural slide activity)
- Risk still very high
- This option does not seem to solve the problem

What to do - Combo of berm construction and trail rehab.?

- This option results in a moderate to high hazard
- low consequence
- moderate risk

Now What?

- Which option should be selected?
- From a risk reduction standpoint - only the first or third options make sense
- When the cost is factored in - only the first option makes sense (berm)

When should the selected option be implemented

- If the risk is truly very high then the selected option should be implemented immediately.
- But what about design and construction issues (where?, how big?, who pays? winter construction...)

Review problem using Judgemental Probabilities and Decision Trees

- Vick and Watts (International Conference on Risk and reliability in Ground Engineering - Bristol, U.K. 1993) presented 3 case histories where the use of Decision Analysis and Judgemental Probability concepts were applied.
- Vick (“ Risk in Geotechnical Practice - 1992”) defines “judgemental probability” as a measure of an individual’s belief based on all information available, be it statistical and data-based, or empirical and experienced based.

Judgemental Probabilities

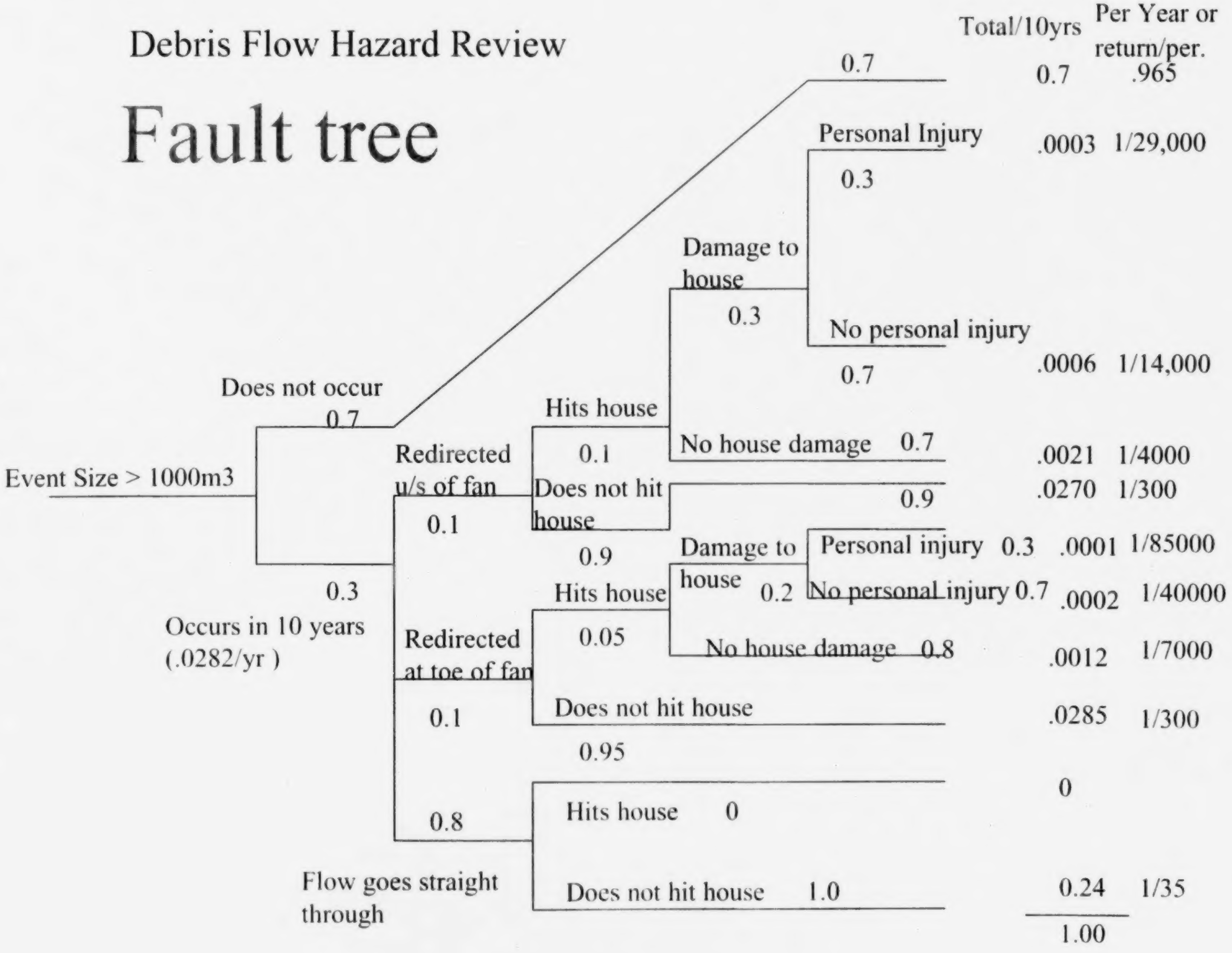
- Judgemental probability is the quantified expression of opinion
- It captures and quantifies the essence of individual experience, and by doing so attempts to address (and in fact improve upon) the shortcomings of statistical probability

Guidelines

- Explicit Guidelines exist for those assessing judgemental probabilities for geologic uncertainties.
- Decomposition
- Consistency
- Limits
- Normalizing

Debris Flow Hazard Review

Fault tree



Event Size > 1000m3

Does not occur 0.7

0.7

Occurs in 10 years (.0282/yr) 0.3

Redirected u/s of fan 0.1

Hits house 0.1

Damage to house 0.3

Personal Injury 0.3

No personal injury 0.7

No house damage 0.7

Does not hit house 0.9

0.9

Redirected at toe of fan 0.1

Hits house 0.05

Damage to house 0.2

Personal injury 0.3

No personal injury 0.7

No house damage 0.8

Does not hit house 0.95

Flow goes straight through 0.8

Hits house 0

Does not hit house 1.0

Total/10yrs	Per Year or return/per.
0.7	.965
.0003	1/29,000
.0006	1/14,000
.0021	1/4000
.0270	1/300
.0001	1/85000
.0002	1/40000
.0012	1/7000
.0285	1/300
0	
0.24	1/35
1.00	

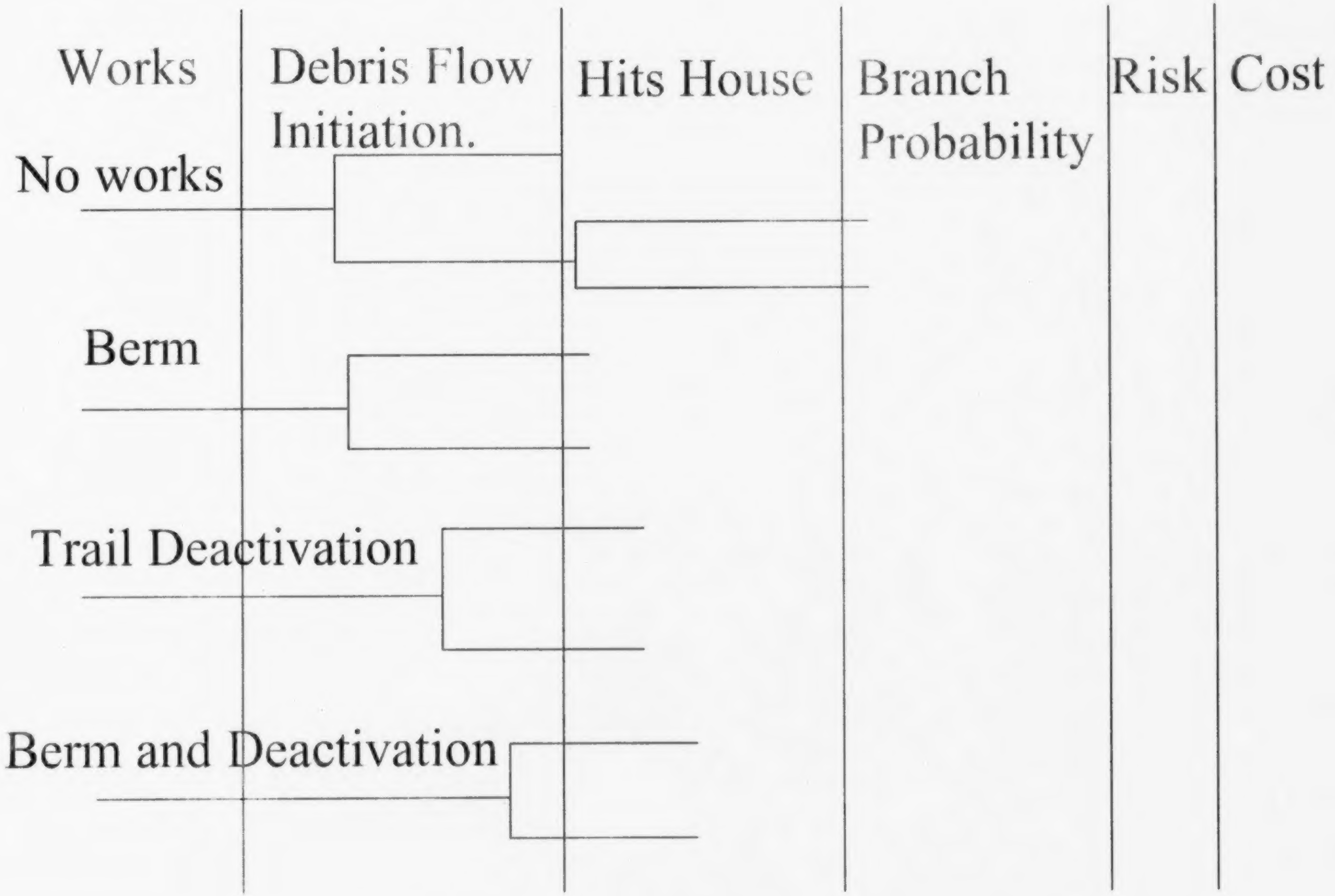
Conclusions

- From fault tree - likelihood of damage to residence is low (1 in 10,000 per year) different result than via the qualitative review.
- The risk equates to a low to moderate risk (very low to low likelihood of impact multiplied by a high consequence).

Recommendations Cont.

- Given the low to moderate risk - it was decided that immediate (during November) works should not be implemented. The hazard associated with a quick implementation of works considered too high. Rather the machine access to and along the trails will be investigated to the determine the requirements, feasibility, and cost of appropriate deactivation.

Decision Tree



Works

Debris Flow Initiation.

Hits House

Branch Probability

Risk

Cost

No works

Berm

Trail Deactivation

Berm and Deactivation

Future Considerations

- If all the fill is removed from the gully and roads deactivated - the hazard may be reduced to about 1/6th. Cost unknown - to be determined
- A berm constructed at the base - would reduce risk to about 1/10th and would provide protection against natural events.
- Once costs determined - compare via cost/benefit comparison.

MASS WASTING EVENTS ASSOCIATED WITH A LARGE MAGNITUDE RAIN-ON-SNOW EVENT, NOVEMBER 1999, COLUMBIA AND ROCKY MOUNTAINS, SOUTHEASTERN B.C.

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ABSTRACT

In November 1999, a large magnitude rain-on-snow event occurred in the Kootenay Region of B.C. In the Columbia Forest District, tens of debris flow, water erosion and other mass wasting events occurred. Many of the in-block debris flows, water events on pre-and post-code roads, and natural events were investigated and site-specific causes determined. Generally, the mass wasting and water erosion events generated by the rain-on-snow were different than typical spring snowmelt-caused events. Surface and subsurface drainage volumes were often beyond ditch and culvert flow capacity. Surface water flow occurred in new, untested locations. Debris flows occurred in the uphill portions of cut blocks and in reactivated gully wall failures. Ice and slush avalanches were observed in alpine areas. This major precipitation event served to pinpoint the locations of inadequate drainage structures and unstable sidecast and road gully fills. The adequacy of drainage structures in new and disused forestry roads is evaluated. The effects of snowpack distribution, cutblock boundaries in relationship to terrain stability polygons and other factors are discussed.

INTRODUCTION

This paper is a compilation of material originally presented as a poster at the Terrain Stability and Forest Management In The Interior of B.C. Workshop, Nelson, B.C., May 23-25, 2001.

The Columbia Forest District is located in southeastern B.C. and includes about 14,000 km^2 between Golden and Revelstoke, extending north to the Mica Dam area and south to Upper Arrow Lake. The area is accessed by the Trans Canada Highway, Highway 95, Highway 23 North and South, and forestry roads (Figures 1 and 2).

On Nov. 9 through 14, 1999, a large magnitude rain-on-snow event impacted the Columbia and Rocky Mountains of southeastern B.C. In the Columbia Forest District, numerous debris flow, water erosion and other mass wasting events occurred (Figures 1 and 2).

The Forest District Engineering staff and the Forest Licensees began assessment and mitigation of erosion problems as soon as possible, accessing by road and helicopter, and directing machine work to restore drainage, clear roads and stabilize slopes. The Ministry of Environment, Lands and Parks was notified of events that impacted watercourses and lakes. District staff conducted helicopter assessments on Nov. 16 north of Revelstoke in the Columbia River and side valleys, and on Nov. 18 north of Golden, where breaks in the cloud cover allowed surface observations.

Many of the erosion sites were field investigated in November and December 1999, and also in 2000, to assess the size, volume, and contributing geologic, hydrologic and land-use factors. Rehabilitation is ongoing at some sites through grass seeding, live branch planting, brush layering, and erosion mat installation.

PHYSIOGRAPHY, SURFICIAL DEPOSITS AND GEOMORPHOLOGICAL PROCESSES

The District includes, from west to east, portions of the Monashee Range, the Purcell Range, and the Selkirk Range, of the Columbia Mountains; the Rocky Mountain Trench; and the Rocky Mountains. Maximum relief is about 2000 m between the peaks and the Columbia River.

The main and tributary valleys are generally U-shaped having been strongly eroded by the Fraser Glaciation valley glaciers. The valley floors are blanketed by till and glaciofluvial/alluvial deposits. The valley sides have till, colluviated till, talus and bedrock outcrops, while alpine areas have large expanses of bare rock and colluviated overburden.

Modern geomorphological processes include debris flows, debris torrents; rockslides, snow avalanches, and stream fluvial processes.

The District includes parts of the Dry, Moist and Wet Climatic Regions of the Nelson Forest Region. Revelstoke weather station is located in the transition between Moist and Wet Climatic Regions, while Golden station is located in the Moist to Dry Climatic Region transition (Table 1).

Table 1. Temperature and precipitation normals for Revelstoke and Golden.

Station	Station Record and Elevation	Daily Mean Temperature (degrees C)	Mean Rainfall (mm)	Mean Snowfall (cm)	Extreme Daily Rain-fall (mm)
Revelstoke (Moist/Wet)	1969 – 1990 443 m asl	6.7	612.2	445.3	43.6
Golden (Dry/Moist)	1902 – 1990 785 m asl	4.6	306.3	184.0	53.3

NOVEMBER 1999 WEATHER RECORDS

The Ministry of Forests, Protection Branch, operates remote weather stations throughout B.C. This data was complied for the Columbia Forest District for the period Nov. 9 to 14, 1999, and rainfall (mm per hour) and temperature (degrees C) trends were plotted (example: Goldstream Remote Station, Figure 3). The remote stations range from valley bottom to mid elevation locations, and are considered representative.

Across the District on Nov. 9, 1999, rain began falling on the early winter snowpack. Between 50 and 150 mm of rain fell on an estimated 100 to 2000 mm of snow. The additional equivalent water depth of snowmelt was estimated to be tens of millimetres.

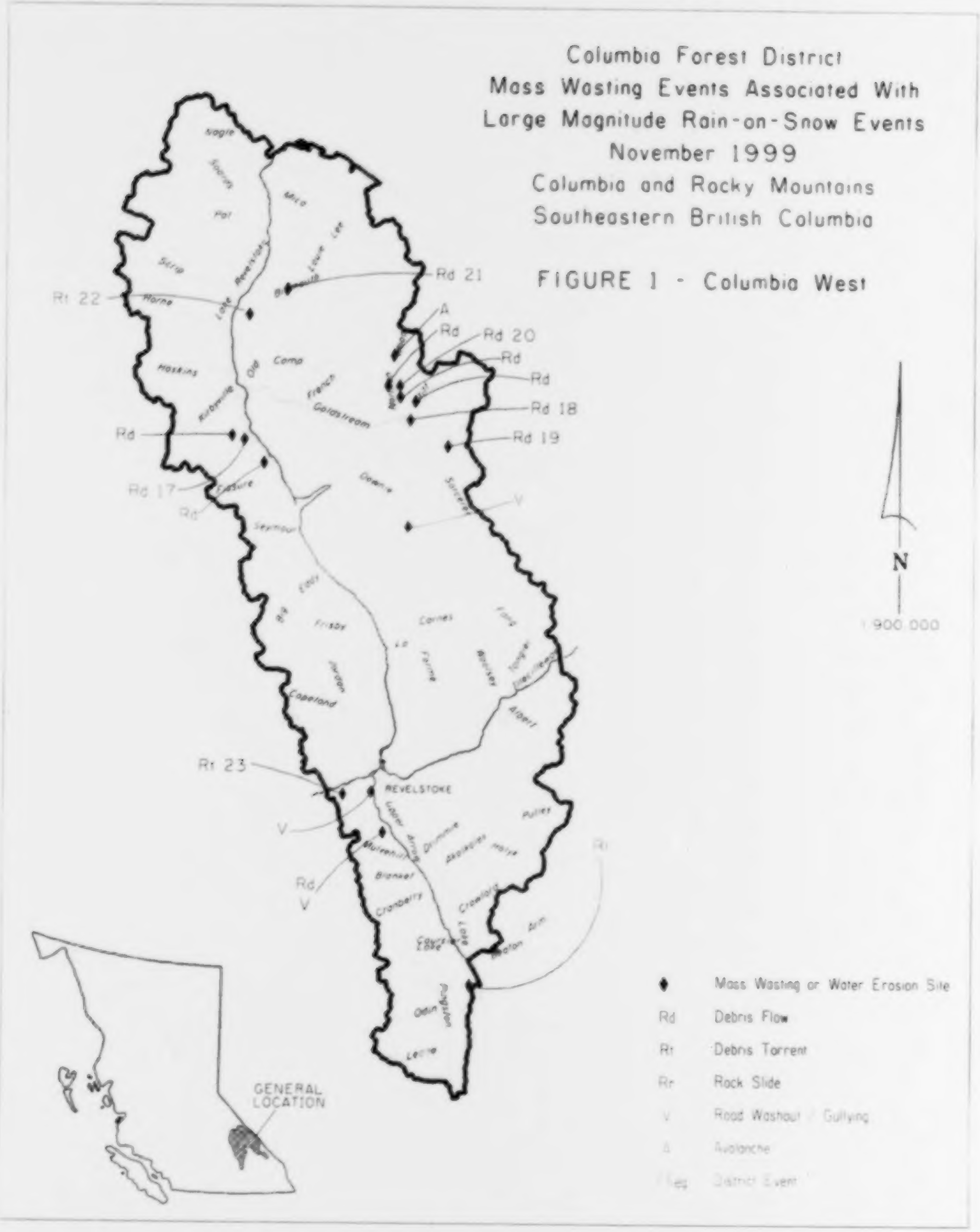

Columbia Forest District
Mass Wasting Events Associated With
Large Magnitude Rain-on-Snow Events
November 1999
Columbia and Rocky Mountains
Southeastern British Columbia
FIGURE 1 - Columbia West
Rd 21
Rt 22
A
Rd
Rd 20
Rd
Rd
Rd 18
Rd 19
Rd
Rd 17
Rd
V
Rt 23
V
Rd
V
Rt
REVELSTOKE
Nagle
Sprague
Pat
Mica
Scrip
Downie
Horne
Lake Revelstoke
Hoskins
Kirbyville
Camp
French
Goldstream
Seymour
Sorcerer
Frisby
Carnes
La Forme
Copeland
Jordan
Albert
Tangier
Illecillewaet
Pulley
Upper Arrow
Blanket
Cranberry
Odin
Pingston
Arrow Lake
N
1:900,000
GENERAL LOCATION
Mass Wasting or Water Erosion Site
Rd Debris Flow
Rt Debris Torrent
Rr Rock Slide
V Road Washout / Gullying
A Avalanche
District Event

Figure 1 - Columbia West. Columbia Forest District: Mass wasting events associated with a large magnitude rain-on-snow event, November 1999.

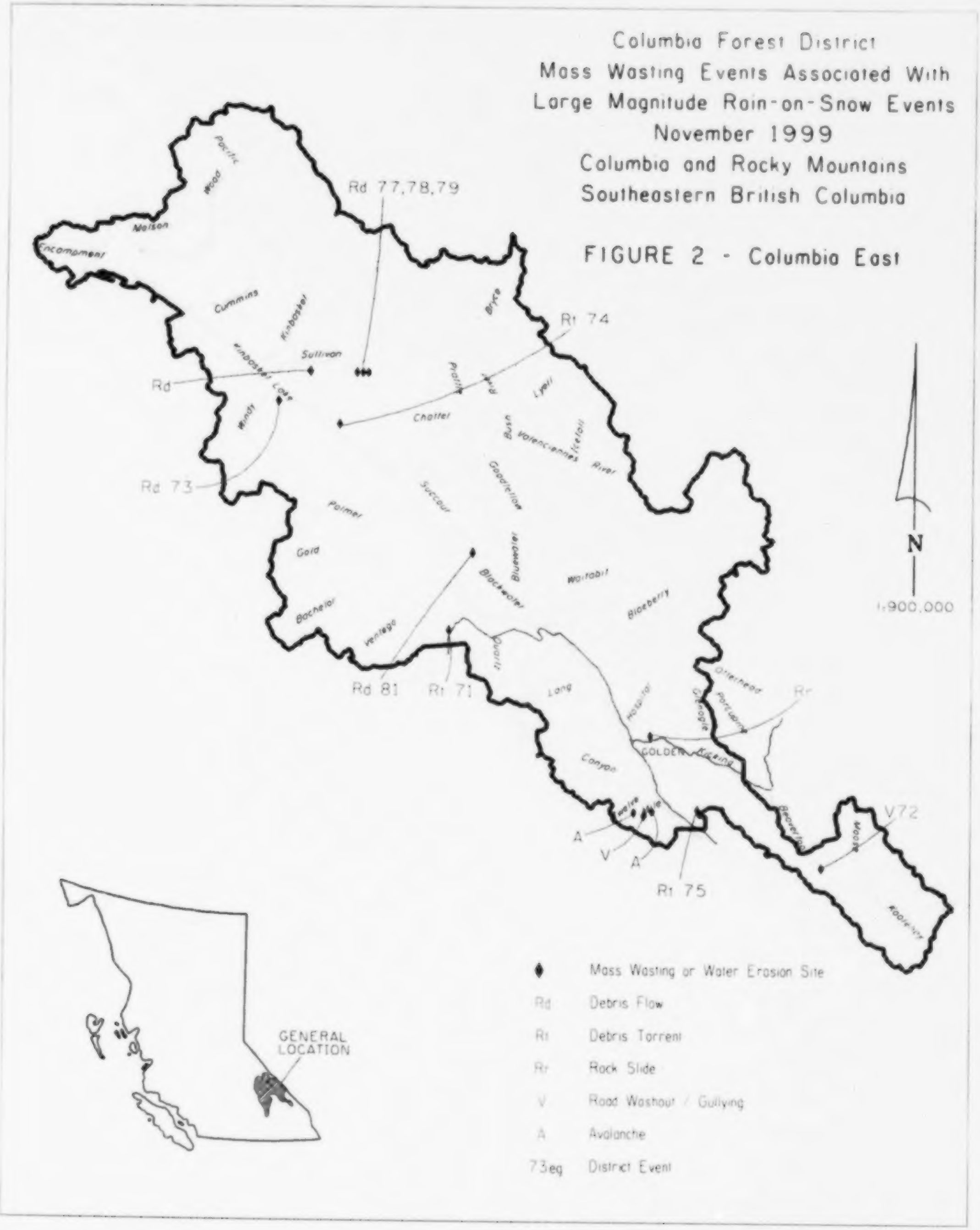

Columbia Forest District
Mass Wasting Events Associated With
Large Magnitude Rain-on-Snow Events
November 1999
Columbia and Rocky Mountains
Southeastern British Columbia
FIGURE 2 - Columbia East
Rd 77,78,79
Rt 74
Rd
Rd 73
Rd 81
Rt 71
Rr
V72
A
V
A
Rt 75
Pacific
Wood
Nelson
Encampment
Cummins
Kinbasket
Sullivan
Kinbasket Lake
Windy
Prattle
Bryce
Lyell
Chatter
Bush
Valenciennes
Icefall
River
Goodfellow
Succour
Palmer
Gold
Bluewater
Blackwater
Waitabit
Blaeberry
Bachelor
Ventego
Quartz
Long
Hospital
Glenogle
Otterhead
Porcupine
GOLDEN
Kicking
Canyon
Beaverfoot
Moose
Kootenay
N
1:900,000
GENERAL LOCATION
Mass Wasting or Water Erosion Site
Rd Debris Flow
Rt Debris Torrent
Rr Rock Slide
V Road Washout / Gullying
A Avalanche
73eq District Event

Figure 2 - Columbia East. Columbia Forest District: Mass wasting events associated with a large magnitude rain-on-snow event, November 1999.

The specific cyclonic weather system was informally described as a tropical storm that combined with a north Pacific low pressure system over the ocean and moved inland over B.C., producing heavy precipitation. The rainfall arrived in intense episodes over about 96 hours, accompanied by 10 to 25 kph southeast to southwest winds. The irregular distribution of precipitation appeared to reflect the variable intensity and size of weather cells embedded in the overall system (Figure 3).

STREAM DISCHARGE

The following stream conditions were noted on Nov. 16 and 18 during the helicopter assessments across the district:

- most creeks and rivers were flowing at high or bankfull stage;
- a few smaller streams and ditches had turbid water, while most others had low to moderate turbidity;
- many small streams and ditchflows had melted through the residual snowpack; and
- groundwater discharge areas had melted through the snowpack, such as on many road cutslopes and old erosion scars.

The Water Survey Branch of Environment Canada operates remote stream gauging stations on some District rivers and creeks. Stream hydrographs for some of the larger watersheds showed 2 to 7 fold increases in discharge over 1 to 2 days (Figure 4, Goldstream River for example), demonstrating the rapid delivery of a large volume of rainfall and snowmelt water to streams. Long-term hydrograph records of the Water Survey Branch showed various short-term hydrograph peaks during October to December. These likely represent other rain-on-snow events. The November 1999 rain-on-snow event was therefore not unique but there were remarkable erosional impacts.

MASS WASTING AND WATER EROSION EVENTS

The Columbia Forest District commonly has 20 to 40 reportable erosion events per year, considerably less per unit area than B.C. coastal areas but a large number for the Interior. This frequency reflects high rainfall, steep slopes, thin overburden, and forestry development in steep slope areas.

The November 1999 mass wasting and water erosion events appear different in type and magnitude compared to the normal debris flows, slumps, road sidecast subsidence, washouts and other events generally associated with spring snowmelt in the District (Table 2).

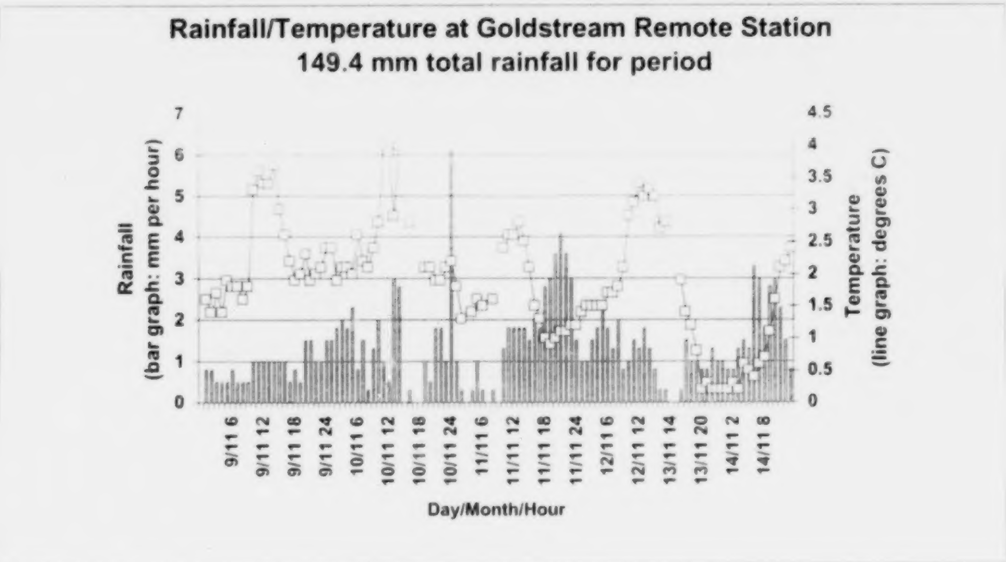


Figure 3. Rainfall/Temperature at Goldstream Remote Station, 149.4 mm total rainfall for period.

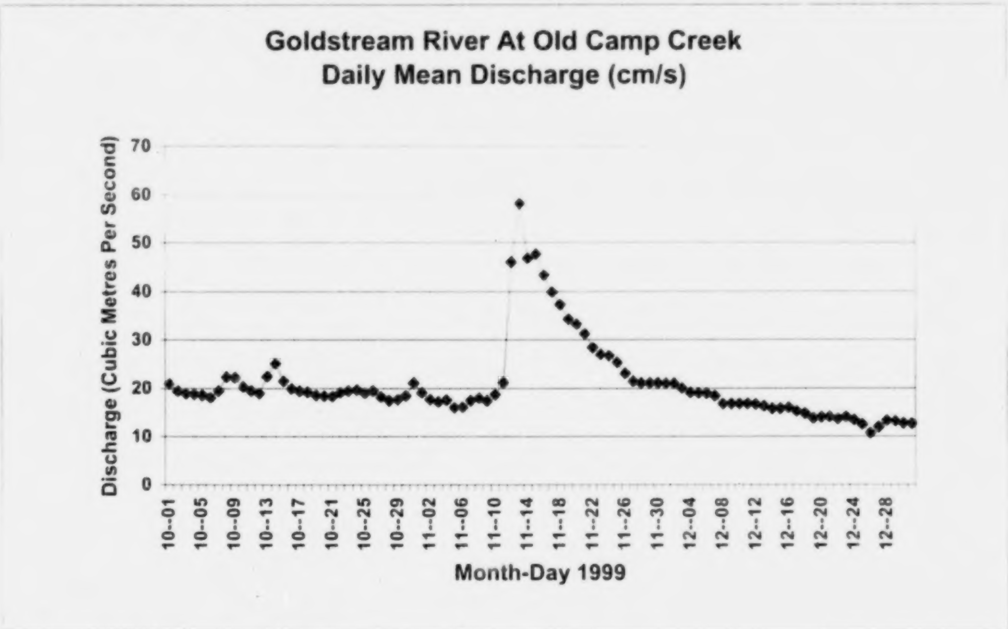


Figure 4. Goldstream River at Old Camp Creek, Daily Mean (cm/s).

Table 2. Columbia Forest District, compilation of mass wasting and water erosion events.

Year	Debris Flow Events	Debris Torrent Events	Water Erosion Events	Other Events	Comments
1996	16	1	11	13	Very high snowpack year.
1997	22	7	15	16	High snowpack and summer convectional rainfall activity.
1998	6	5	2	6	Low snowpack year.
1999 April-Oct.	36	4	11	1	Many small events related to high summer convectional rainfall activity.
1999 Nov.	26	7	7	6	Regional rain-on-snow event (Nov. 9 – 14))
2000	10	3	1	4	Average snowpack year.
2001	6	1	4	1	Dry spring and summer.

Numbers are approximate due to changing criteria/thresholds for reporting over time, and changing administrative areas.

The rain-on-snow event resulted in:

- shallow, inblock debris flows;
- road sidecast and gully wall failures into streams, which initiated debris torrents;
- high volume, erosive surface water flows over land, in ditches, on roads, and in streams;
- drainage capacity problems where high flow overwhelmed the snow and ice-filled ditches, and culverts and roads were overtopped; and
- temporary perched water tables and high soil moisture content produced by excessive surface water flow and in-situ snowmelt on slopes.

Debris Flows

Most debris flows in cutblocks were small (less than 20 m wide and 50 m long), shallow (less than 1 to 2 m) and occurred in weathered, permeable overburden over unweathered overburden with lower hydraulic conductivity. These debris flows occurred on the steep in-block slopes, often immediately below the upper cutblock boundary, or at the site of previous debris flows (Photos 1 – 4). The cutblocks were generally several years old, cable harvested, and had plantations. No mass wasting was noted in adjacent forested land of similar slope and overburden conditions. The major impact of these debris flows was loss of plantations and soil resources.

The rain and snow meltwater flux reduced soil bearing capacity in many areas sufficiently to initiate failures, such as on sidecast or old debris flow deposits. The size and shape of failures appeared to reflect the transient water table configuration, and areas of soil water flux.

The steepest in-block areas commonly failed but had not been classified as Unstable in previous terrain stability assessments. The upslope edges of cutblocks usually end at steeper slopes, with shallow overburden and lower tree density, which are often the boundaries of Potentially Unstable or Unstable terrain polygons. It is possible that the deeper snowpack in the cutblocks, resulting from the lack of canopy interception and sublimation, and the higher wind loading, led to higher snowmelt volumes delivered to the weathered surficial overburden. Loss of root strength with rot in the several year old cutblocks may also have reduced overall soil strength and therefore the slope stability.

Debris flows also occurred where gully walls or road sidecast failed, depositing on gentler slopes or into streams below.

Debris Torrents

At least 7 debris torrents occurred during the rain-on-snow event, more than the typical number for spring or summer conditions. The Watask FSR (Rt 23, Figure 1) and Bush-Sullivan FSR (Rt 74, Figure 2; Photo 5) events may have started as snow or slush avalanches that eroded gully bottoms and road prisms such that debris torrents were generated. The Bigmouth FSR (Rt 22, Figure 1; Photo 6), and Rogers Road (Rt 71, Figure 2; Photo 7) events started from ditch and road surface water which caused road sidecast failure, and in turn entered steep, flowing streams and torrented. The torrent near Liberty Creek (Photo 8), the Campbell Road torrent (Rt 75, Figure 2) and the Bannock Creek torrent near Shelter Bay (Figure 1) appear to have started from natural gully wall failures entering streams.

Avalanches

The avalanches noted were in established chutes and consisted of slush flows and ice and snow falls carrying some soil (Photo 9). These were more frequent than usual in early winter. Rain likely fell at the highest elevations, affecting a considerable vertical range of snowpack.

Water Erosion Events

On some older forestry road systems, discharge overwhelmed ditches and culverts and resulted in water flow over and down the road or onto slopes with no alluvial tracks, sometimes resulting in further mass wasting. Examples include Upper Begbie FSR south of Revelstoke (Figure 1) and Beaverfoot FSR (V72, Figure 2) events.

Early winter snow and ice filled most forestry road ditches and culvert inlets, reducing flow capacity. Roads which had snow plowed into the ditches were also affected. On some older roads, inadequately-sized culverts, and culverts which received many inflow streams, caused water erosion events.

DISCUSSION AND CONCLUSIONS

During the November 1999 rain-on-snow event, debris flows and torrents, avalanches and water erosion events were more frequent than during normal spring snowmelt and runoff, or during summer convectional rainfall events. The distribution of the mass wasting and water erosion events appeared to reflect the intensity and duration of rainfall and snowmelt, generated by the weather cells of variable intensity and size embedded in the cyclonic system. The erosion events were generally gully-forming and extension processes.

The rain-on-snow event was an extreme test of the road drainage system capacity, and the stability of constructed slopes. In many places, older road drainage systems appeared inadequate, and will need to be improved as road redevelopment occurs. Most newer, engineered slopes remained stable however some older road sidecast slopes failed. Most deactivated roads remained stable and had adequate drainage, indicating that the engineering prescriptions were appropriate.

Compared to typical spring snowmelt conditions, there were fewer slumps, and sidecast subsidence features, suggesting there was no deep penetration of the wetting front from rainfall and snowmelt, but possibly the formation of temporary perched water tables, that may have been atop frozen soil layers. These temporary perched water tables may have initiated shallow debris flows.

It is interesting to note that the rain-on-snow conditions generated mass wasting and water erosion events in gullies and on slopes. These gullies and slopes were generally old, relict landforms. These relict landforms may have been originally eroded when rain-on-snow events were more common in the postglacial climatological regime.

ACKNOWLEDGEMENTS

The contributions and assistance of Brian Mallett, Doug Lagore, Ken Minty, Val Beard, Steve Mitchell, Norm Koerber, Peter Jordan and Laura Richardson of the Ministry of Forests, and Lynne Campo of Water Survey Branch, are gratefully acknowledged. Phil Kor and Donna Bird provided editorial comments.

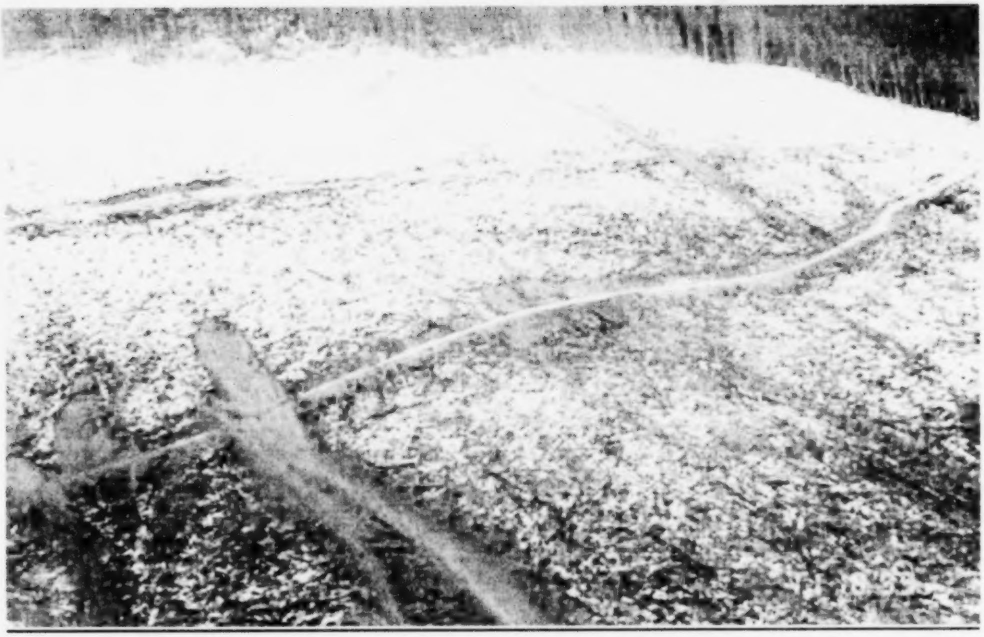


Photo 1. Re-activated shallow debris flows and streams melted through snowcover, Sullivan River area.

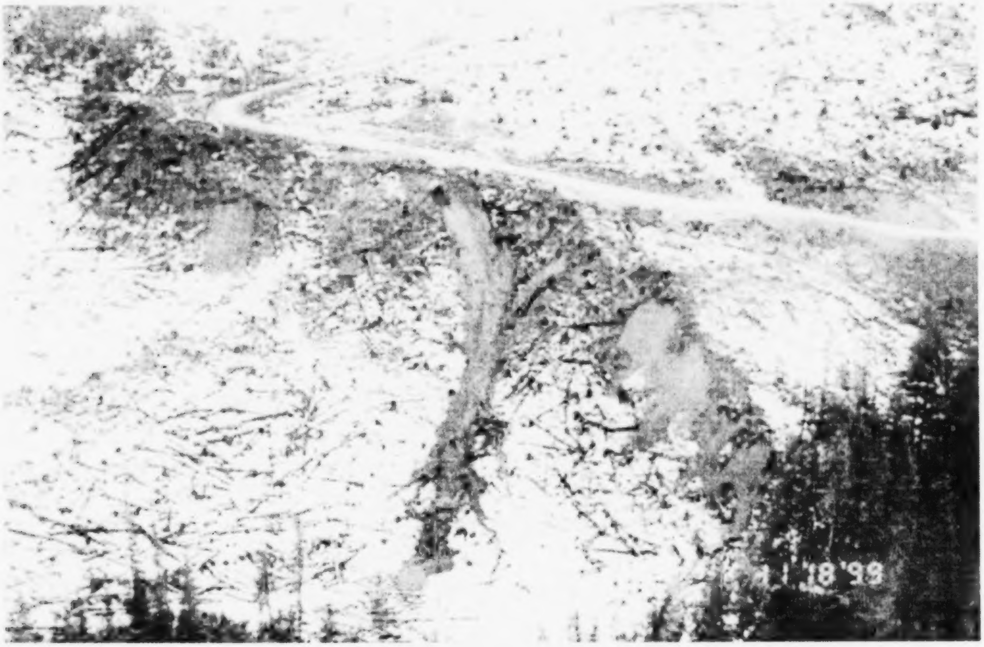


Photo 2. Shallow debris flows from natural slopes and road sidecast, Sullivan River area.

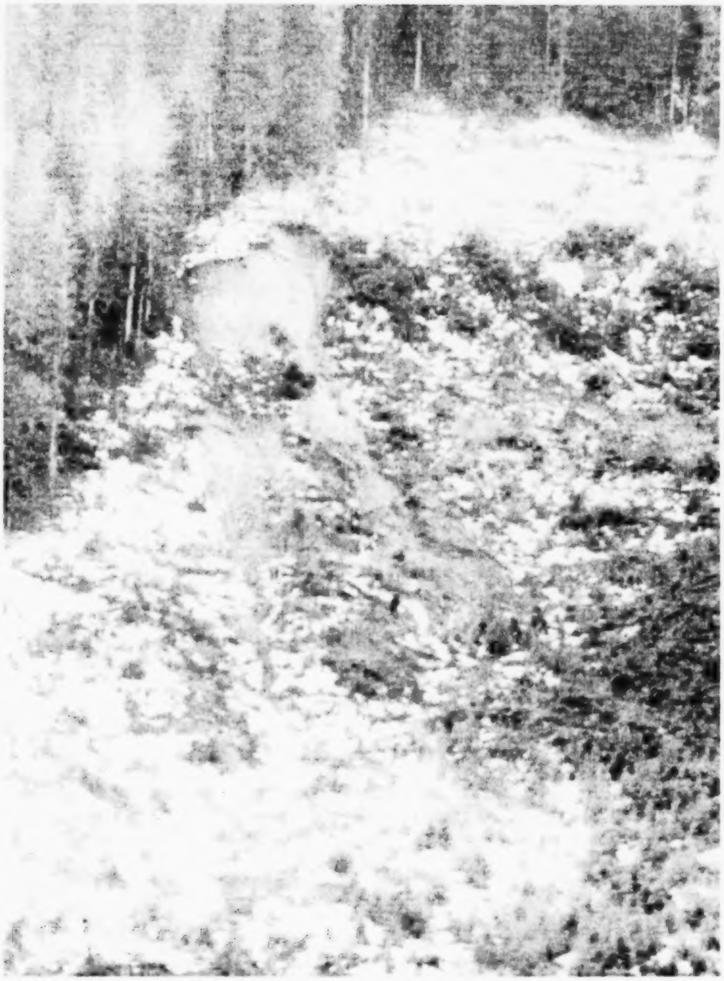


Photo 3. Shallow debris flow and melted water tracks in cutblock north of Liberty Creek, north of Revelstoke.

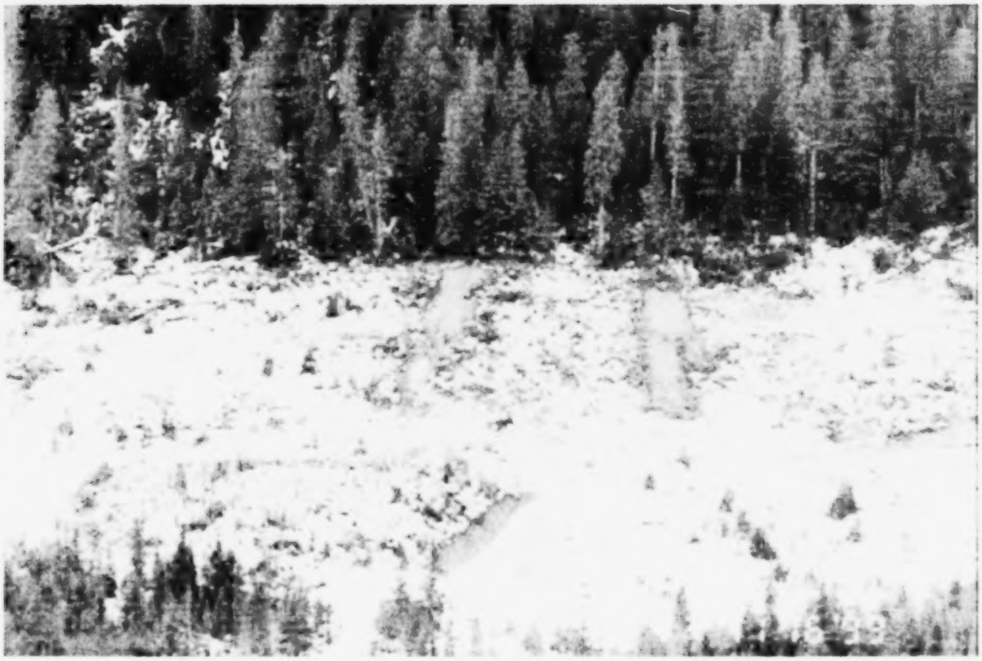


Photo 4. Shallow, inblock debris flows, Bigmouth Creek area.

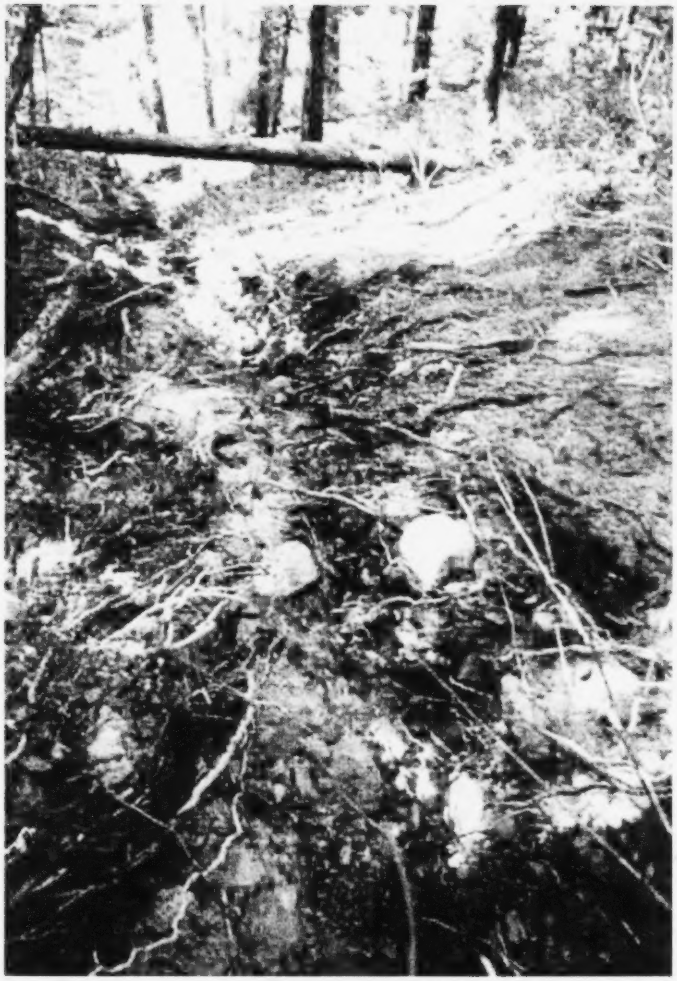


Photo 5. Gully with evidence of water erosion and vegetation press (slush flow?), Bush-Sullivan FSR area. A torrent occurred further down this gully.

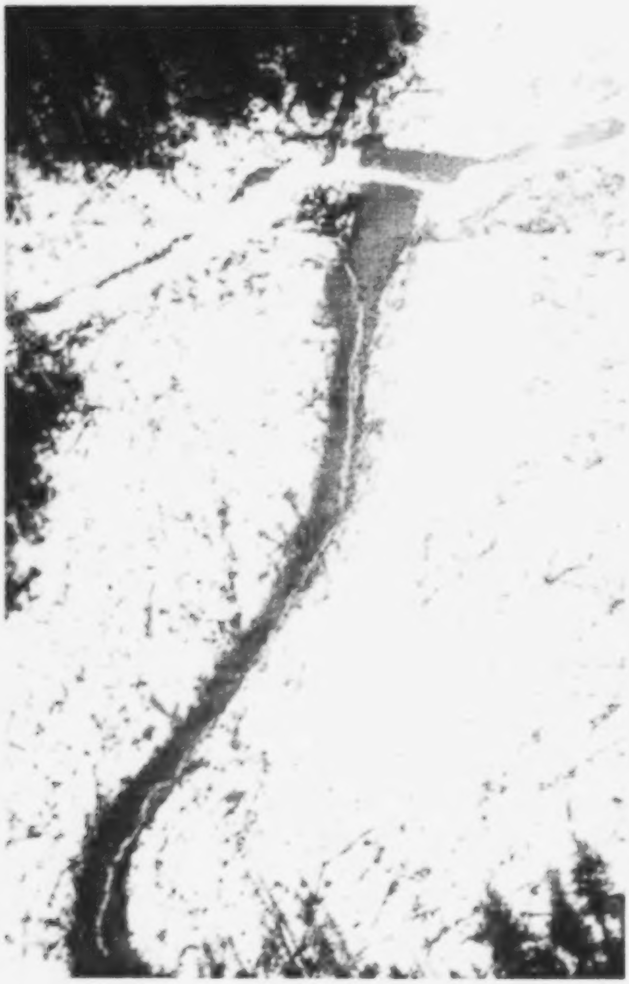


Photo 6. Debris torrent caused by gully fill/sidecast failure, Bigmouth FSR area. (Doug Lagore photo)

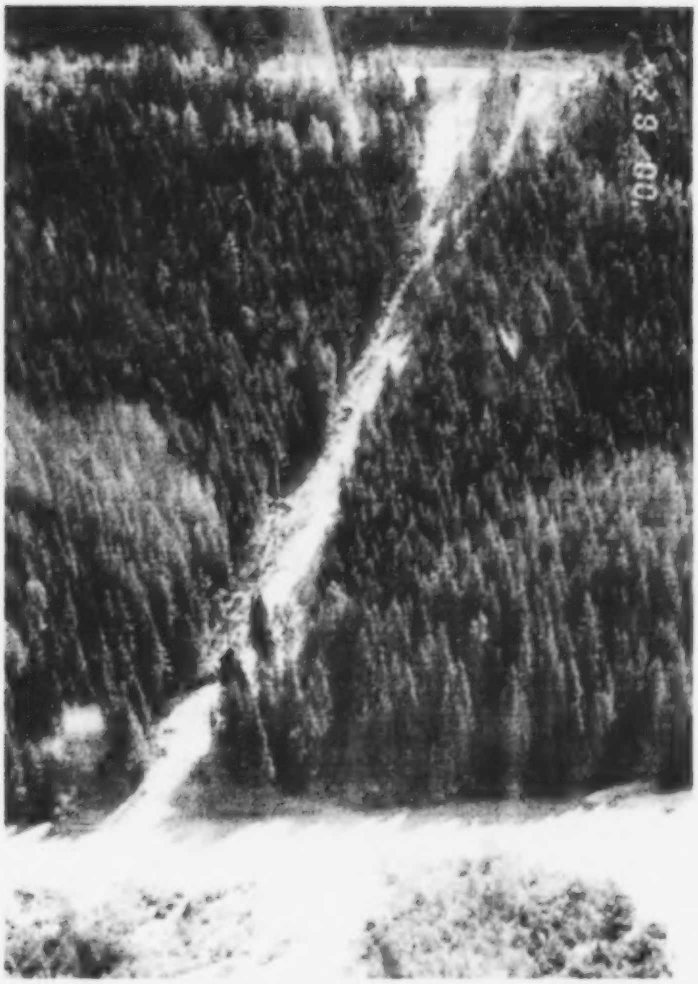


Photo 7. Rogers Road debris torrent, northwest of Golden, which deposited into Beaver River (Mark Turner photo). Grass cover and erosion control mats visible as darker green tones on lowermost part of scar.

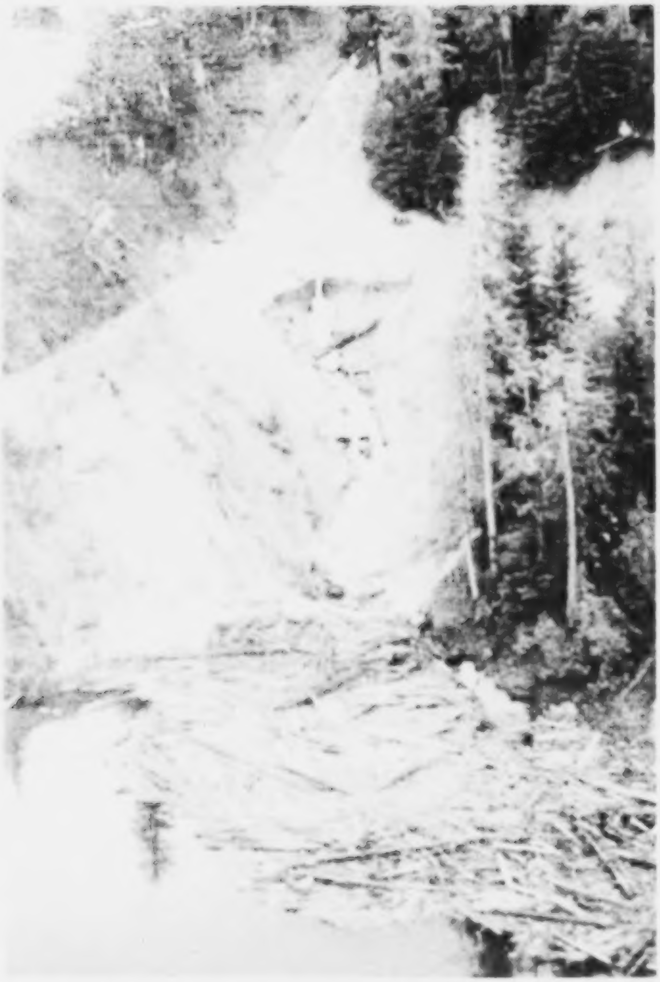


Photo 8. Creek north of Liberty Creek which had gully wall failure and torrented, depositing onto road and into Lake Revelstoke.

Photo 9. Unusual wet, plug-type avalanche with subsequent snow/ice ball avalanche, 12 Mile Creek area, southwest of Golden. (Norm Tihor photo).

Causes of Gentle-over-Steep Landslides in Arrow and Kootenay Lake Forest Districts

PETER JORDAN AND DOUG NICOL

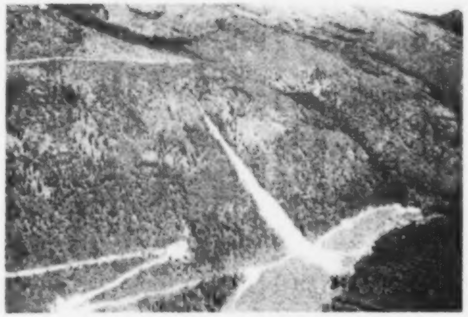
ABSTRACT

In the southern Interior of British Columbia, many landslides related to forest development occur on steep slopes below roads and cutblocks that are on relatively gentle terrain. An important problem in planning forest development is that Forest Practices Code requirements for terrain stability assessments and road design are based on conditions at the site, not on the often more hazardous slopes below.

We have investigated a number of landslide incidents throughout the Nelson Forest Region, including many below cutblocks and roads. Some of these have occurred below "post-Code" roads (those built since the introduction of the Forest Practices Code in 1995). This presentation will focus on several landslides in the Arrow Forest District which illustrate the hydrological and geotechnical processes involved in landslide initiation, as well as the forest planning implications. Two main mechanisms will be discussed: drainage concentration and diversion by roads, and enhanced snowmelt due to clearcuts above potentially unstable slopes.

Causes of Gentle-over Steep Landslides in Arrow and Kootenay Lake Forest Districts

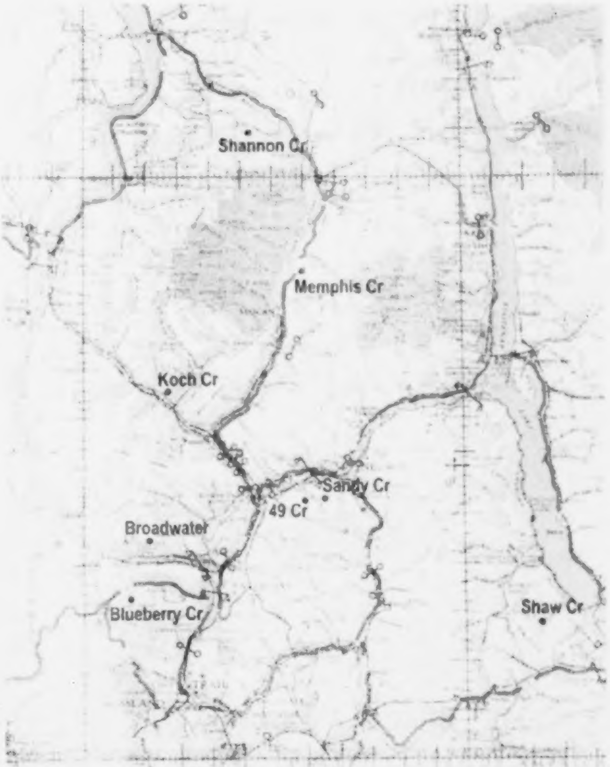
Peter Jordan and Doug Nicol, B.C. Ministry of Forests, Nelson

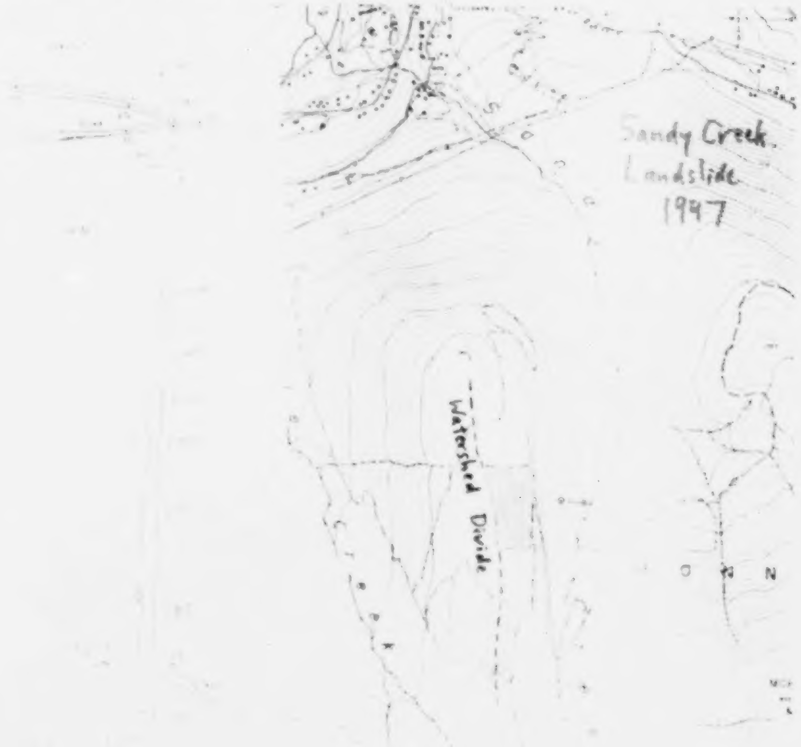


Shaw Creek, TF 40 (private), Kootenay Lake Forest District

Sandy Creek landslide, May 1997.

The slide started at the break in slope below a culvert, and a cutblock logged about 8 years earlier. The cutblock occupies the entire drainage area above the culvert. Causes were concentration of water by the road, a wide culvert spacing (200 m), and enhanced snowmelt in the clearcut.


Shannon Cr
Memphis Cr
Koch Cr
Sandy Cr
49 Cr
Broadwater
Blueberry Cr
Shaw Cr


Sandy Creek
Landslide
1997
Watershed Divide
N

Shaw Creek, TF 40 (private), Kootenay Lake Forest District

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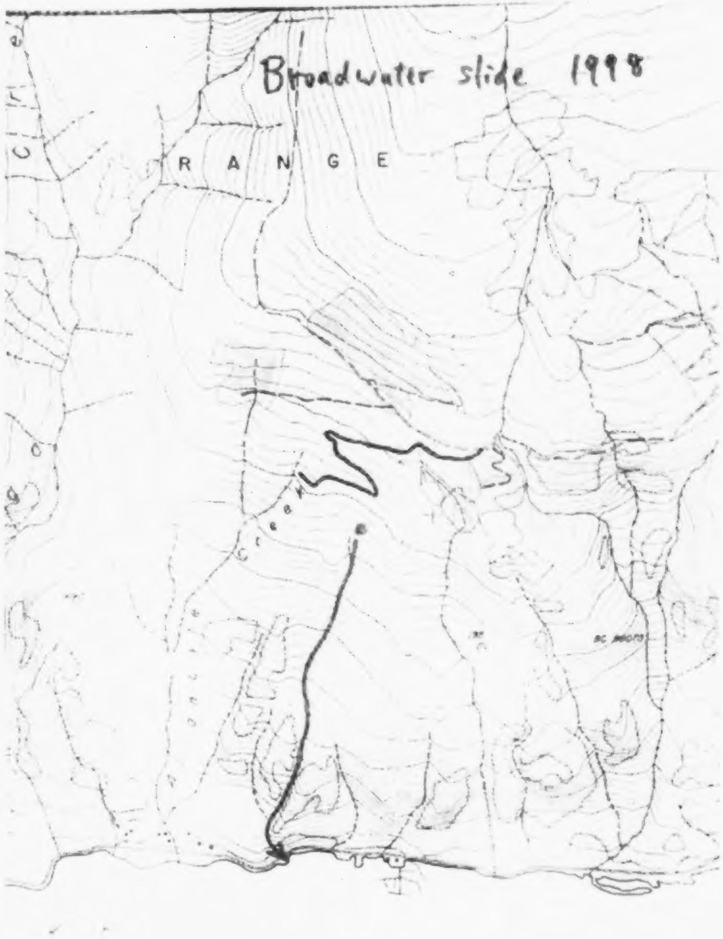
Shannon Cr
Memphis Cr
Koch Cr
Sandy Cr
49 Cr
Broadwater
Blueberry Cr
Shaw Cr

Watershed Divide

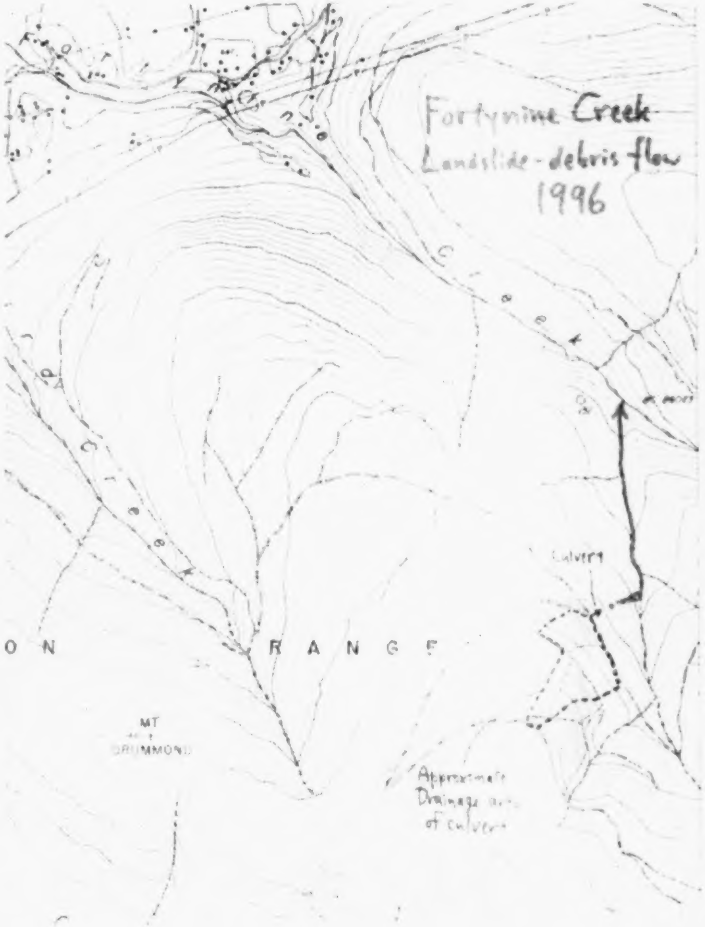
Broadwater Road landslide and debris flow, May 1998.

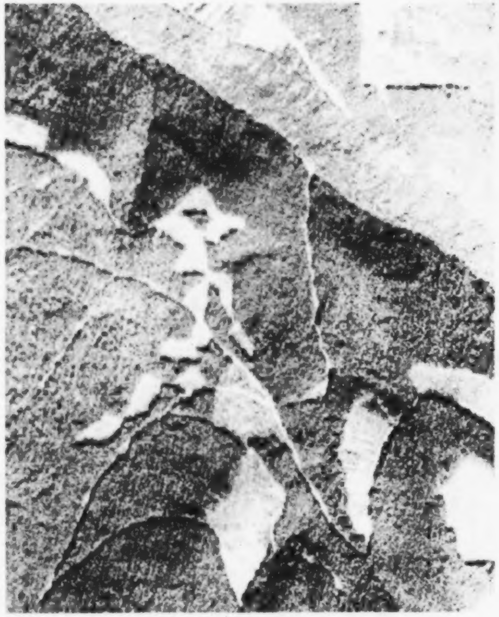
The slide occurred about 150 m below a road built in 1997. It was caused by water diverted from its natural course about 20 m to a switchback. There was also deactivation in older logged areas upslope in 1997. The slide became a very large debris flow, which traveled down a steep gully to Lower Arrow Lake.



Fortynine Creek landslide and debris flow, May 1996.

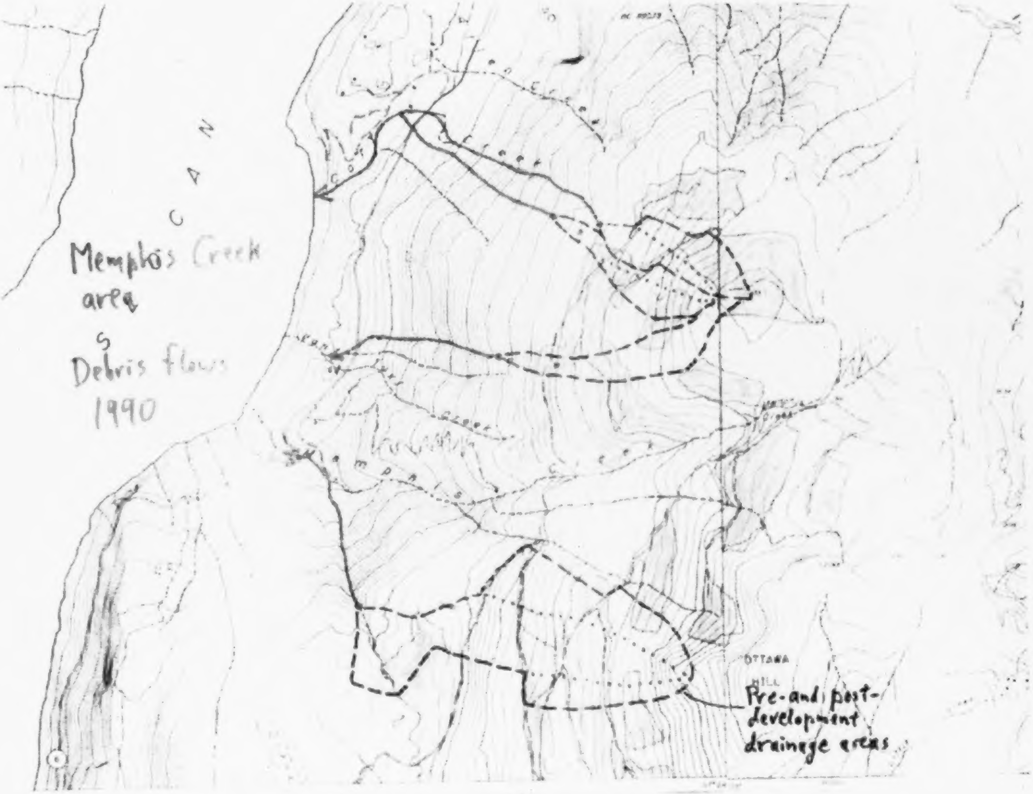
The slide started at the break in slope below a culvert. The main cause was concentration of water by the road. Enhanced snowmelt in clearcuts, and drainage diversion of water by skid trails, were probably minor factors. The debris flow was very large, and added much sediment to the creek, causing damage to several water intakes.


Fortynine Creek
Landslide-debris flow
1996
Creek
Creek
Culvert
O N
R A N G E
MT
DRUMMOND
Approximate
Drainage area
of culvert

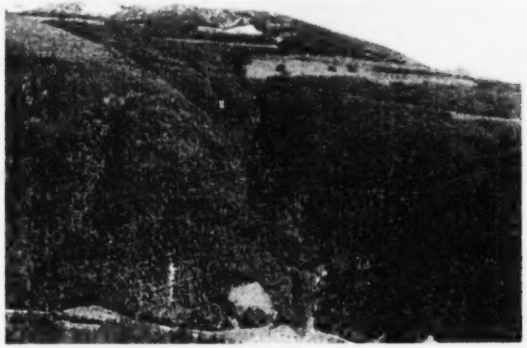


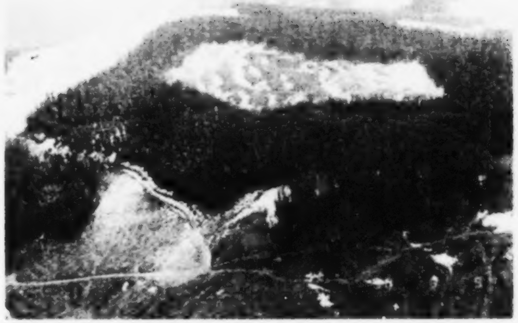
Memphis Creek area, debris flows of May 1990.

Four debris flows occurred during a rain-on-snow event, below an area which was logged in the 1970s. The roads and skid trails had not been deactivated. There was damage to the highway, private property (a house was narrowly missed), water intakes, and a small hydro plant. The main causes were interception and concentration of drainage by roads and skid trails, and increased drainage area due to flow diversion above three of the slides. Increased snowmelt rates in clearcuts was a minor cause.



Memphis Creek area
&
Debris flows 1990
CAN
Memphis
OTTAWA HILL
Pre-and post-development drainage areas

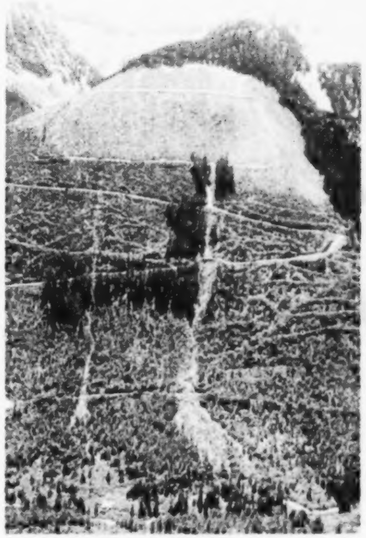




Shannon Creek, June 1999.

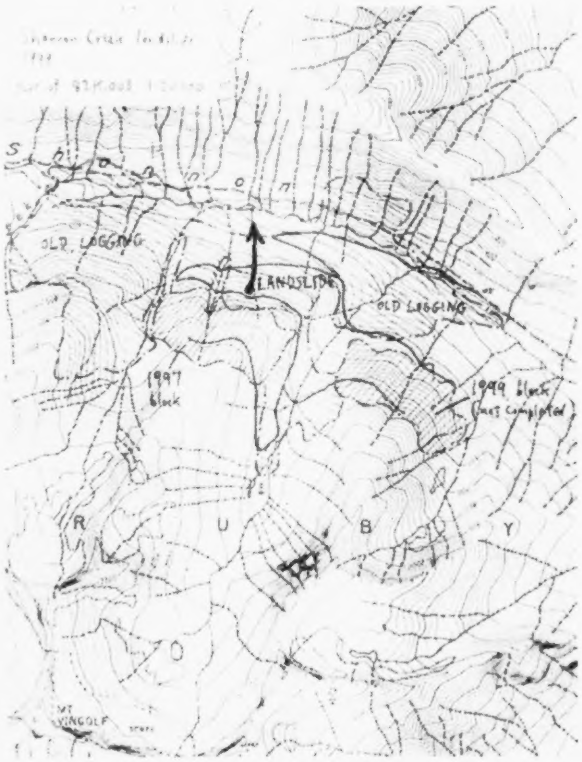
Although this is not a "gentle-over-steep" example, it illustrates some of the common causes of landslides below roads and cutblocks. The slide started as a fill failure in an old skid trail, below a culvert on a recently reconstructed road. The culvert was placed about 40 m down-road from the centre of a gully. The ditch and culvert intercepted subsurface flow from the gully and diverted to the failure point. Diversion of water by old skid trails was also a factor. As about 90% of the drainage area upslope is clearcut, with the recent large cutblock logged in 1979, increased snowmelt is probably also a factor.

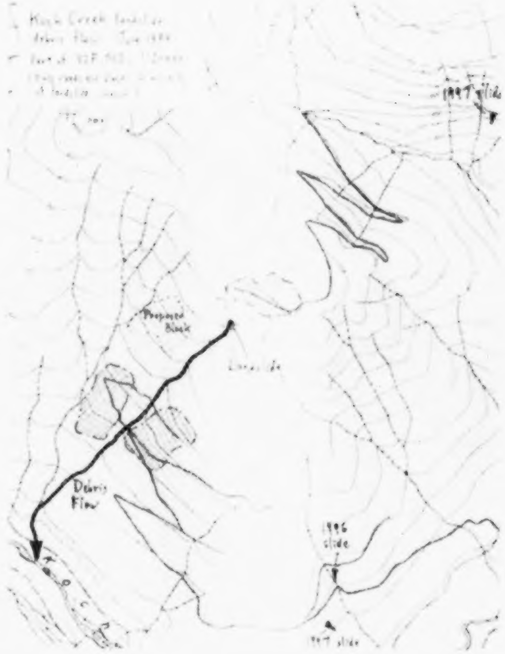
(The landslide is on the left of the photo. The feature on the right is a snow avalanche which originated in the cutblock.)



Koch Creek, June 1999.

This slide started at a break in slope about 350 m below a cutblock logged in 1994, and traveled as a debris flow 2.5 km to the valley bottom. Causes were a poorly located culvert, concentration of drainage by a spur road, failure to deactivate the road following logging, and enhanced snowmelt in the clearcut.


S
OLD LOGGING
LANDSLIDE
OLD LOGGING
1997 block
1999 block (not completed)
R
U
B
Y
MT YINGOLF


1997 slide
Proposed Block
Landslide
Debris Flow
1996 slide
1997 slide

Memphis Creek area, debris flows of May 1990.

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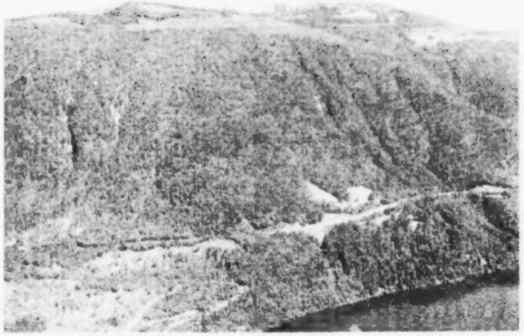
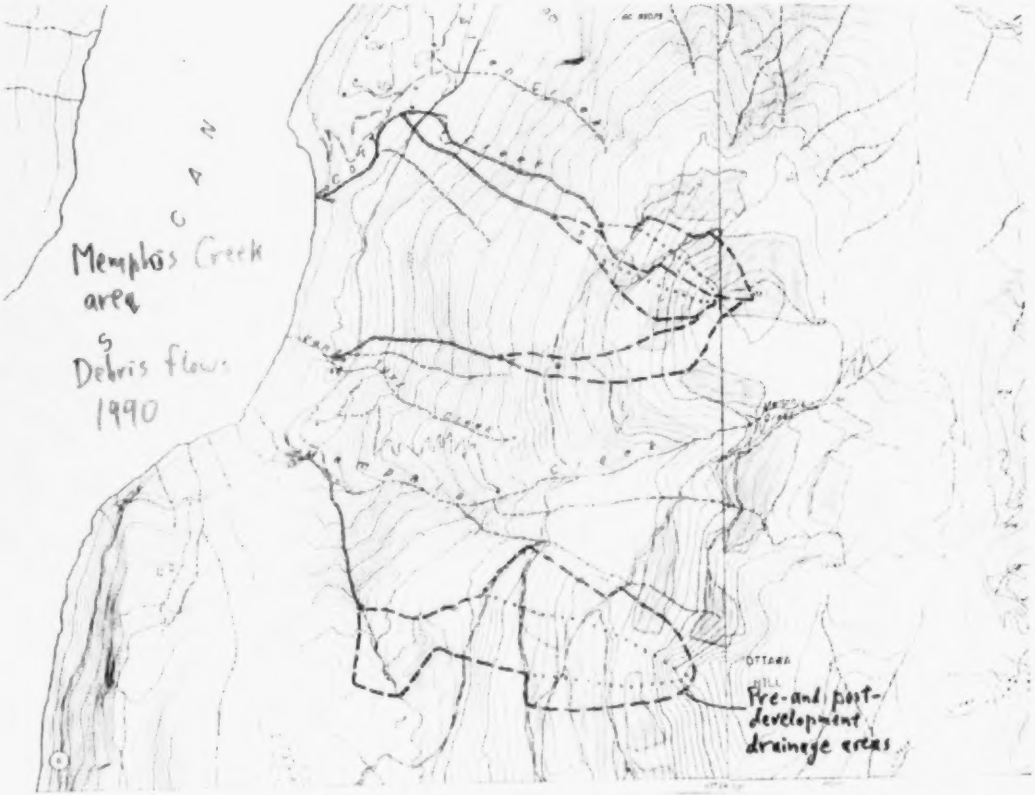
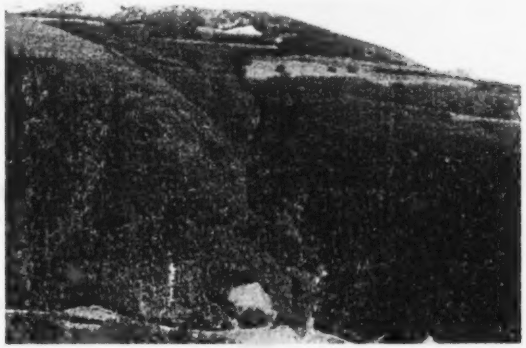



Memphis Creek area & Debris flows 1990
OTTAWA HILL
Pre-and post-development drainage areas



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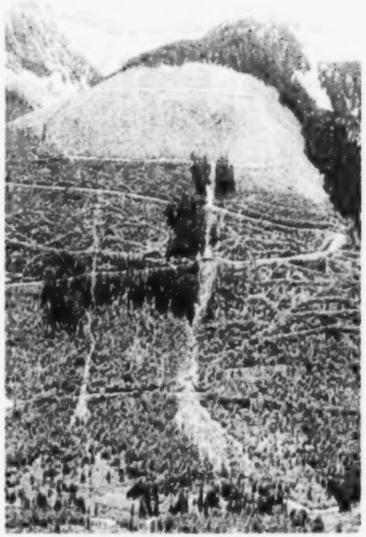

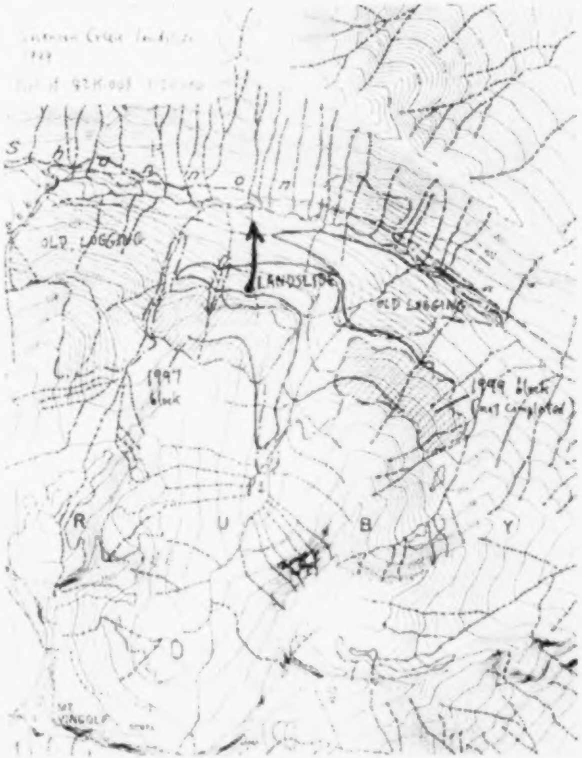
S
OLD LOGGING
LANDSLIDE
OLD LOGGING
1997 block
1999 block (not completed)
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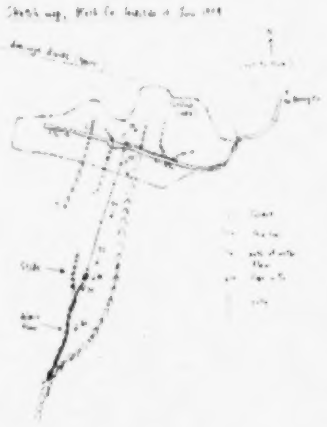
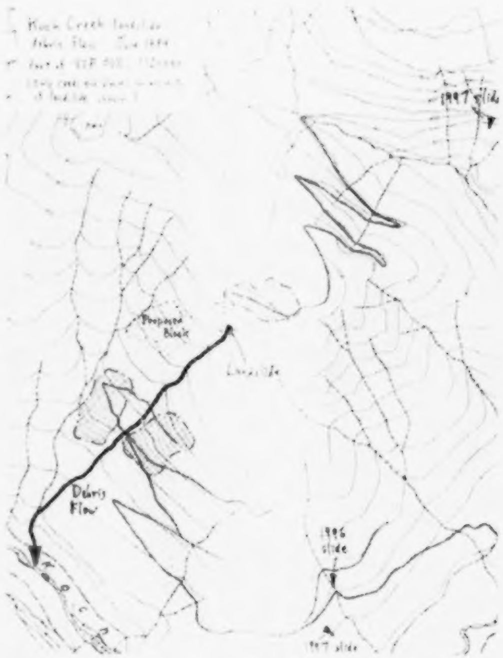
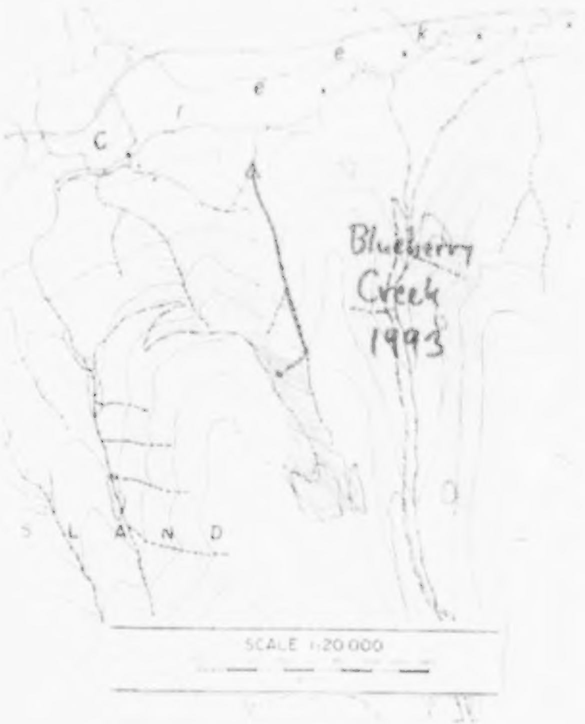
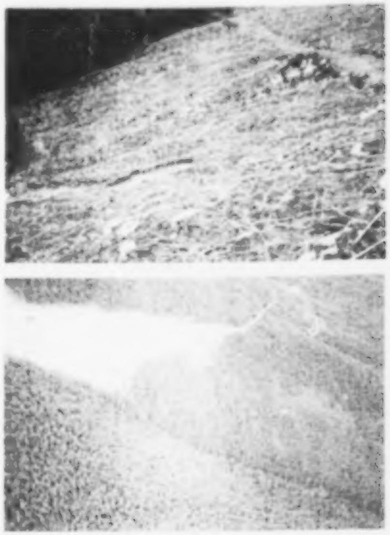



1997 slide
Proposed Block
Landslide
Debris Flow
1996 slide
1997 slide


C r e e k
S L A N D
Blueberry Creek 1993
SCALE 1:20 000

Blueberry Creek, May 1993.

This event started as a small landslide at a subtle break in slope below a culvert. It continued as a large debris flow, nearly reaching Blueberry Creek. The cross-drain culvert had been placed about 10 m to one side of a natural drainage hollow, in order to coincide with a low spot in the road. It is typical of many slides which occur below poorly-placed culverts or cross-ditches, and illustrates how flow diversions of only several metres can cause large landslides.



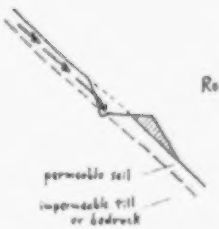
Conclusions.

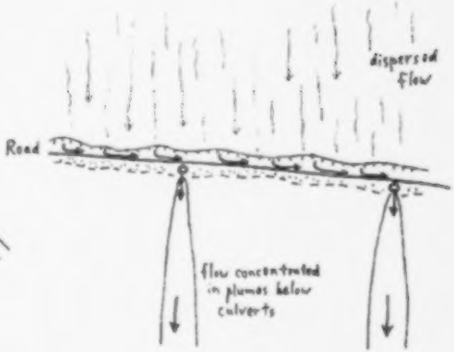
These examples illustrate two main causes of gentle-over-steep landslides:

Concentration and diversion of runoff by roads. The first figure at right shows how naturally dispersed, shallow, groundwater flow can be concentrated by culverts. The second fugure shows how a landslide can occur at the break in slope below a point of concentration of flow.

Increase snowmelt in clearcuts above a point of landslide initiation. In most of these examples, 50 to 100% of the drainage area above the point of drainage concentration had been clearcut. However, enhanced snowmelt alone has not been implicated as the sole cause of landslides; in all cases, concentration or diversion of the runoff by a road was also a factor.

It is worth noting that all these landslides, except the Memphis Creek examples, occurred in terrain that would likely be mapped as stability class III by most terrain mappers.


permeable soil
impermeable till or bedrock


dispersed flow
Road
flow concentrated in plumes below culverts

COFFEE CREEK LANDSLIDES AND FLOOD EVENT OF NOVEMBER 1999

Nichole Boultbee, Doug Nicol, P.Eng., Peter Jordan, P.Geo.
B.C. Ministry of Forests, Nelson
and Dwain Boyer, P.Eng.
B.C. Ministry of Environment, Lands, and Parks, Nelson.

On November 11 and 12, 1999, an unusual rainstorm caused flooding and landslides in several areas of the Kootenay region of British Columbia. The area most affected was the Coffee Creek drainage near Balfour, on Kootenay Lake, where serious damage occurred to Highway 31. Several landslides occurred in the watershed, and the forest service road along the creek was washed out at many locations.

The relative importance of natural processes, and landslides and erosion caused by forest development, is an issue that is always raised whenever a damaging hydrologic event occurs. In Coffee Creek, a large landslide in an old cutblock was caused by the rainstorm, and a large natural debris flow occurred in an undeveloped area nearby. Both events added large quantities of sediment to the creek channel, and downstream from these slides, the channel experienced severe bank erosion and aggradation.

Severe fall rainstorms are very unusual in the Kootenays, where almost all peak flows as well as landslide and erosion events, occur during spring snowmelt. Information on the climatic and hydrologic causes of the event, and the natural and forestry-related landslides, will be presented.

This presentation is based to a large extent on these sources:

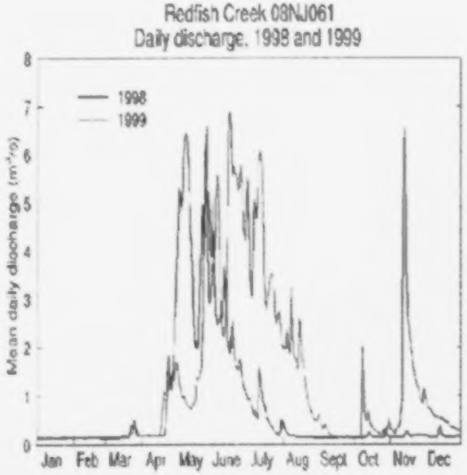
Boyer, D. and P. Jordan. 2001. *November 1999 Fall Rainstorm: Kootenay Region.* Paper prepared for Canadian Water Resources Association, BC Branch Conference, May 8-11, 2001, Whistler, B.C.

Nicol, D. 2000. *MOF Review of the November 12th, 1999, Coffee Creek debris slides, slumps, and debris flow.* Report prepared for Kootenay Lake Forest District, January, 2000.

Coffee Creek Landslides

Nichole Boultbee, Doug Nicol, Peter Jordan (MoF, Nelson) and Dwain Boyer (MoELP, Nelson)

The Storm


Redfish Creek 08NJ061
Daily discharge, 1998 and 1999

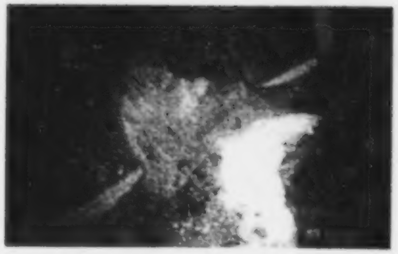
On November 11-12, 1999, an unusual fall rainstorm occurred in the Kootenay region, with the greatest rainfall and damage at Coffee Creek. At many streamflow stations in the region, the peak discharge greatly exceeded any previously recorded fall discharge. For total storm rainfall, the return period of this storm for the fall season is estimated at about 1 in 100 years, and on an annual basis at about 1 in 40 years. Snowmelt contributed about 30 mm of additional storm runoff to the 2-day rainfall of 108 mm. As a comparison, the town of Kaslo generally receives an average of 69mm of rain and 22 mm (SWE) of snow in the month of November, and the maximum recorded 1-day rainfall in any month was 51 mm.

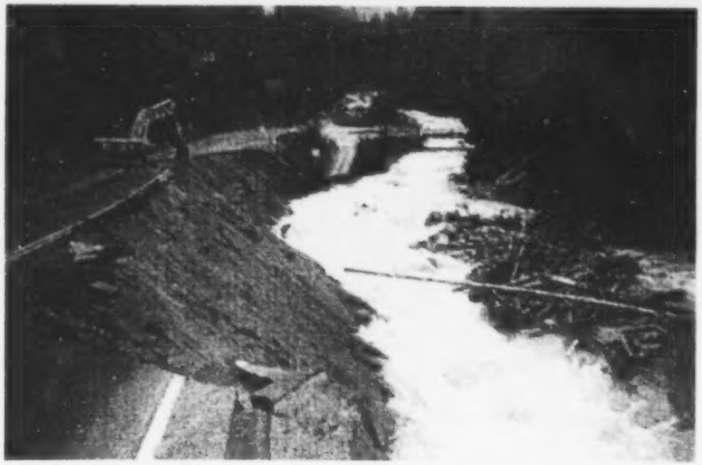
On Redfish Creek, adjacent to Coffee Creek, the maximum 1-day discharge was about a 2-year flood on an annual basis. However, on Coffee Creek, the return period was probably much greater, based on flood damage and failure of bridges. On West Kootenay gauging stations, up until 1999 the annual peak always occurred during the spring freshet. It is extremely unusual for a fall rainstorm peak to

Storm precipitation, November 9-13, 1999 (mm)
(note: daily reporting periods vary)

STATION	1-day	2-day	5-day
Kaslo MSC (ca 580 m)	29	61	82
Coffee Creek MOTH (625 m)	80	108	140
Redfish Alpine (2080 m)	72	113	192

The Roads



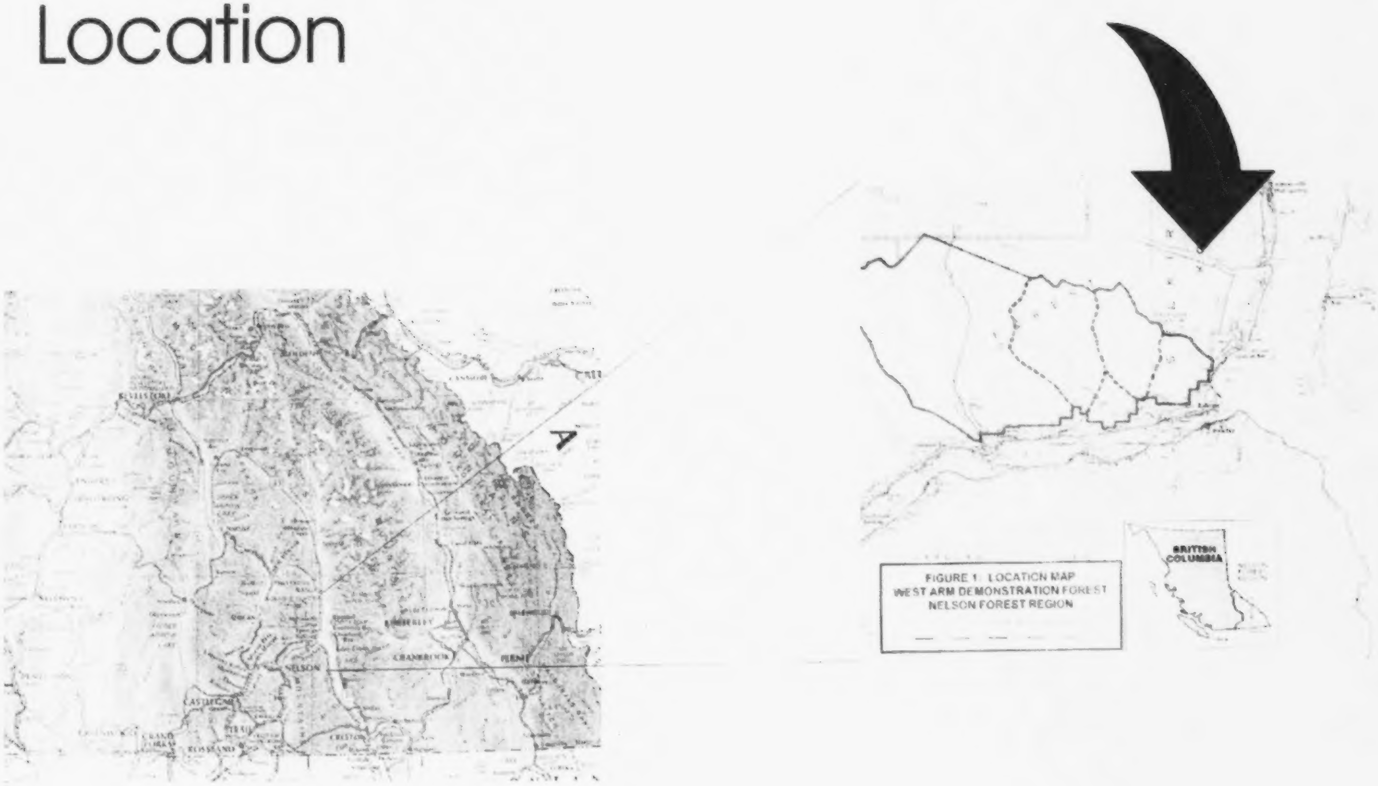


As a result of the storm significant damage was incurred by the forest service road, Highway 3A, and a park access road. The forest service road was washed out in many places, and the damage was estimated at $500,000. A segment of the highway was destroyed, and the traffic was restricted to one lane for several months.

The forest service road is currently not usable, and other temporary access to the drainage is being used. The forest service road will be permanently deactivated in the future.

Location

Location

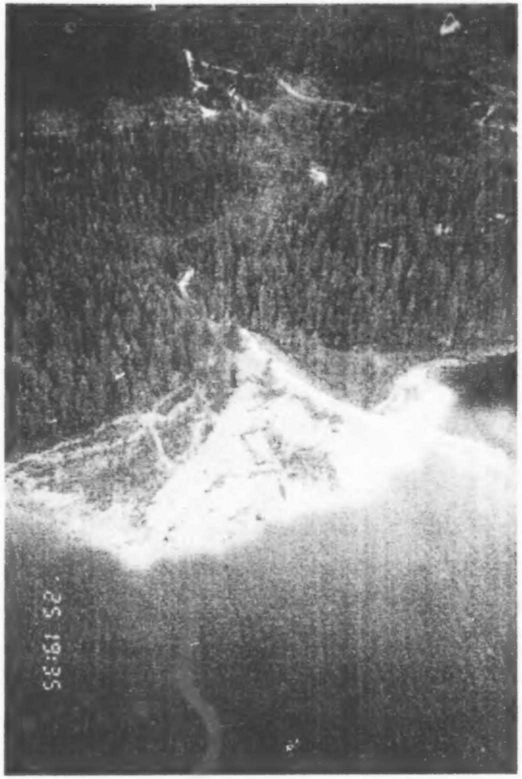

A
REVELSTOKE
KIMBERLEY
CRANBROOK
NELSON
FERNIE
CASTLEGAR
TRAIL
ROSSLAND
CRESTON
FIGURE 1. LOCATION MAP
WEST ARM DEMONSTRATION FOREST
NELSON FOREST REGION
BRITISH COLUMBIA

Landslides

As a result of the storm at least 10 landslides were initiated. Some of the landslides were natural, while others were a result of water diversions off of roads and skid trails. In both cases, the extreme rain was the main contributing factor to the landslides.

One very large landslide in an old cutblock, approximately $20,000m^3$, deposited large volumes of debris into the creek. From this point downstream, the creek experienced a debris flood, which aggraded and widened its channel. A large natural debris flow also contributed much sediment near this point. Because of the debris flood and the road washouts it caused, some people were stranded in the drainage overnight.

Present Channel



The Coffee Creek channel was significantly altered as a result of the high water flows during the storm, and also due to landslides adding sediment to the channel. Extensive aggradation of the channel bed occurred, and many road washouts and slope failures occurred as the creek attempted to widen its channel. There are many banks that are currently being undercut and are slumping into the creek. These banks will continue to input sediment into the creek for a long time.

In some locations, large piles of woody debris accumulated along the channel. A salvage operation was conducted to recover timber washed into Kootenay Lake.

RECENT LARGE MAGNITUDE LANDSLIDES, PRINCE RUPERT FOREST REGION

James W. Schwab
Prince Rupert Forest Region, B.C. Ministry of Forests, P.O. Bag 5000, Smithers B.C. V0J 2N0

Abstract

Large magnitude landslides occur on an infrequent basis within the interior portion of the Prince Rupert Forest Region. Where these large landslides occur they have considerable impact to forestland. Four recent large landslides were investigated:

1. Windfall main landslide (Mezidian Lake) was caused by the diversion of creek 300 meters down a logging road (7,000 m^3 / 20 hr period). Water flowed into a bedrock fault in sedimentary rock. The failure initiated as a bedrock slide of 100,000 m^3 that triggered a debris avalanche, which travelled 900 m. to the valley flat—It carried boulders the size of pickup trucks. Total volume transported is in the order of 160,000 m^3. Land area covers 14 hectares.

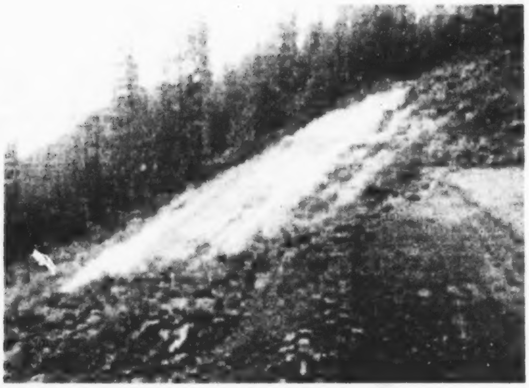
2. Rock avalanche Howson Range (Telkwa pass) originated as a rock topple failure ($1.0X10^6$ m^3) from a rock ridge. The rock fell about 150 meters onto glacial ice, expanded to cover the ice valley glacier, a width of 300-400 meters, continued down the ice valley and avalanched into the Limonite Creek valley. The rock avalanche travelled a total distance of 2.6 km dropping 1,300 m in elevation and severed the PNG pipeline. The avalanche path through mature forest covered and area 1,200 meters long by 400 meters wide. This area was scheduled for harvest through the SBFEP. Historical rock avalanches have occurred in the Limonite Creek valley. The level of acceptable risk must be considered for forestry operations in potential rock avalanche zones.

3. A retrogressive slide-flow occurred on relatively gentle, completely forested, seemingly benign terrain proposed for timber harvesting (Goat Mountain, Harold Price watershed east of Smithers). Failure was within a deep compact basal till. The landform was dissected by a few minor ephemeral stream channels. There was no evidence of previous large landslides. The landslide covers an area of 6.1 ha. Volume is in the order of 250,000 m^3. The headscarp of the failure bowl is 24-28 m deep. Sliding occurred along an assumed failure plane of 24%. Morphological features resemble failures in sensitive clays. The till is similar to glacial tills found through out the Bulkley Valley (LL 33.5, PL 12.1, PI 21.4, sand 41.8%, silt 31.0%, clay 27.2%, and bulk density 1.85). The gentle slope and the lack of discernible field indicators suggest that a failure at this site may not have been anticipated through a routine terrain stability field assessment.

4. A large underwater landslide ($3x10^6m^3$) occurred off the steep slope of a fan-delta on Troitsa Lake. The visible portion of the landslide measures 400 m by 60 m. A displacement wave 1.5 m high hit the opposite side of the lake one kilometre away. A backwash wave 2 m in height crashed back over the head scarp. The north end of the lake (10 km from the landslide), experienced an initial sharp swell about 60 cm in height; bays and shallows where then sucked empty. A large return wave 2 m high crashed through a shallow bay, tearing sunken logs and debris from the bay floor and hurling the debris on to the beach and into the forest surrounding the bay. Boats and floating wharves were ripped from their moorings. The instability of fans and fan-deltas in freshwater fjord-type lakes is mentioned briefly in published literature. However, little documentation exists of known sites and landslide-tsunami events in British Columbia.

Posters on these four events (reduced to fit 8.5" X 11" paper) follow.

Meziadin Rock Slide - Avalanche

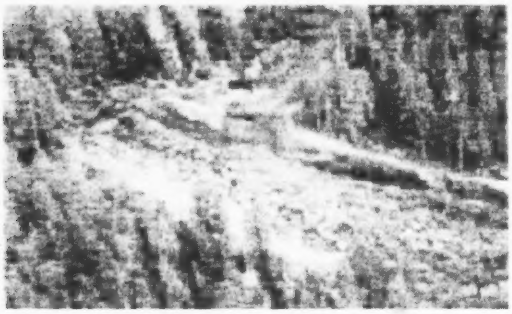


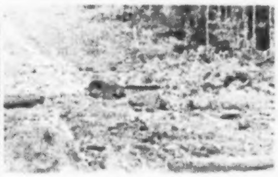
Introduction

A rain-on-snow event occurred on September 28 and 29, 1992

A backhoe operator dispatched to clean out a plugged culvert noted that the road felt mushy. He radioed a logging truck traveling down the road immediately behind him. The truck driver responded by stopping his truck. He walked around the corner and discovered that the road was gone.

The landslide removed 75 meters of the road up to 20 meters deep and cut a 200 by 900 meter long swath, destroying 14 hectares of mature timber.



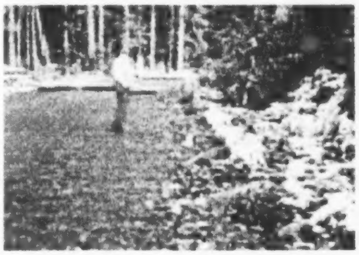


Hydrology

An undersized and partially plugged culvert resulted in the diversion of water 300 meters down the road surface and ditch to the landslide site.

No culverts were found along the road for the 300 meter distance adding flow from two additional small drainage basin.

The water diverted from the larger drainage basin of 94 hectares drained onto a site with no previous natural surface drainage An increase in drainage area by 10 time.



Water delivered to the soil surface in the 20 hours preceding the landslide was modeled to be 69 mm, at a peak hourly rate of 6.8 mm/hour.

The delivery rate of water for the rain-on-snow event was equivalent to a 10-year rainstorm.

A total volume of about 7000 m^3 of water was delivered to the initiation zone of the landslide at a maximum rate of 42m^3 second

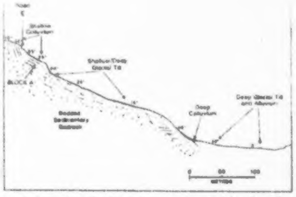
Failure Process

The water diverted down the road spilled into the site of a bedrock fault that bounded the failure. Water also entered cracks in the bedded sedimentary rock.

The forces from water pressure within faults and cracks resulted in decreased stability of the rock mass.

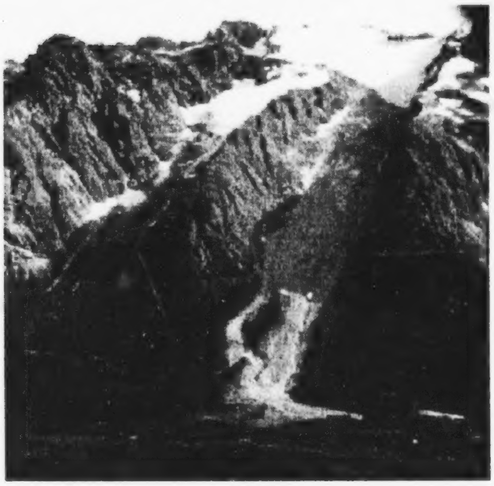
Initial failure was a bedrock slide of 100,000 m^3 that triggered a debris avalanche.

Total volume transported 160,000 m^3.



Glacial action left an unsupported bedrock block in an upper slope position, on bedding planes, dipping at an angle of 32 degrees.

Rock Avalanche - Howson Range Telkwa Pass



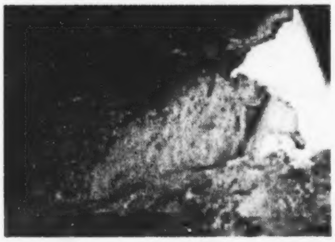
Introduction

At 03:00 hours on Saturday September 11, 1999 a large rock avalanche severed Pacific Northern Gas pipeline through Telkwa Pass, 50 km west of Smithers and a like distance east of Terrace, B.C.

Considerable glacial ice loss has occurred over the past 50 to 150 years within the ice valleys, exposing over steepened valley walls.

The ridges between the glaciers extend up to 300 meters in height and are composed of highly fractured and near vertically jointed granodiorite bedrock.

Landslide Description



The rock avalanche originated as a topple failure from a bedrock ridge (approximate size 900,000 m^3).

The rock toppled and slid about 150 meters onto glacial ice, expanded to cover the ice-valley glacier to a width of 300-400 meters, continued down the ice valley then avalanched into Limonite Creek valley. The rock avalanche travelled a distance of 2.7 km, dropping 1,300 meters in elevation.

The avalanche path through mature forest covered an area 1,200 meters long and up to 400 meters wide.

The avalanche incorporated and transported a total volume in the order of 3 to 5 million m^3.

Landslide debris dammed Limonite Creek, creating a lake that filled within a few days.

Rock Avalanche Hazard

The presence of highly unstable, unsupported rock ridges and the geomorphic evidence of past landslides suggest that the potential for other large rock avalanches exists.

Risk to Forest Operations-Limonite Valley

The forest within the September 1999 rock avalanche path was scheduled for timber harvesting. Similar sites elsewhere in the valley are also proposed for harvesting. A landslide could be triggered by ongoing deformation and displacement of the rock, seismic activity, and precipitation from snow melt or heavy rainfall. Also, the instability along the unsupported rock slopes adjacent to the ice valleys will likely increase with further melting of glacial ice. We do not know when another rock avalanche will occur or down which ice valley glacier it could travel. Forest development within potential rock avalanche tracks thus places workers at risk. Landslide hazard, in the context of probable occurrence and consequence as related to time of exposure ,becomes an important variable in determining relative risk. Should workers be informed of the hazards and possible consequences? At what point is the risk deemed unacceptable? Without calculated probabilities for events, is acceptable or unacceptable risk a personnel decision or should the sites simply be precluded from forest harvesting?

Goat Mountain Flow-slide

Introduction

This retrogressive slide-flow occurred on relatively gentle, completely forested, seemingly benign terrain proposed for timber harvesting in the Harold Price watershed (July 19,1999).

There was no evidence of previous large landslides.

Precipitation for May and June 1999 was 150% above normal.

Failure was within deep compact basal till.

The headscarp is 24-28 m deep.

The landslide covers 6.1 ha.

Landslide Features

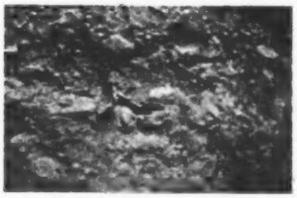
Morphological failure features resemble failures in sensitive clays.

Common features: tilting and fracturing of subsiding wedges; intrusion of 'spoil' upwards in clefts between wedges and prisms.

Collapsed Wedges, Ridges, and Prisms:

found at mid and lower landslide positions

Glacial Till



The compact glacial till is similar to other glacial tills found through out the Bulkley Valley—inorganic clay of medium plasticity.

Liquid Limit 33.5
Plastic Limit 12.1
Plasticity Index 21.4
Bulk Density 1.85.

Minerology

Clay	Silt
Kaolinite	Quartz
Chlorite	Feldspar
Smectite	Kaolinite
Mica	Laumontite
Quartz	Smectite
	Mica

Particle Size

Sand	41.8%
Silt	31.0%
Clay	27.2%

Gravel content 40%

Ground Surface Before and After Failure

Assumed failure plane 24%
Pre-slide surface
Post-slide surface
Total Distance— 550 meters

Tsunamis on Trotisa Lake

Introduction

Picture yourself in a small bay at the end of a long narrow lake bounded by steep mountains—Troitsa Lake.

Suddenly a sharp swell enters the bay; not an abnormally large storm-size wave. Seconds later, water is sucked from the bay leaving boats and debris stranded.

With a tremendous roar a large wave returns tearing boats from their moorings, smashing into the shore carrying debris 20 meters over the beach and up into the forest surrounding the bay.

The water subsides but the lake remains unsettled, with many progressively smaller waves pulsing back and forth throughout the day.

On the morning of October 6, 1998 a tsunamis was triggered by a large underwater landslide that occurred off the steep slope of a fan-delta.
The visible portion of the landslide measures 400 m by 60 m along the edge of a fan-delta surface.

This visible face is the head scarp and upper slump block of a large landslide that extends down the steep face of the delta to depth in Troitsa Lake.

Estimated volume: three million cubic meters.

Tsunamis Wave

A displacement wave 1.5 m high hit the opposite side of the lake one kilometer away.

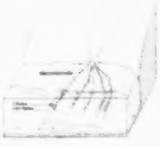
Groups of large trees matted together were rafted by the wave up to one km across the lake.

A backwash wave two meters in height crashed back over the head scarp carrying debris up to 150 m inland over the delta surface.

The north end of Troitsa Lake (10 km from the landslide) experienced an initial sharp swell about 60 cm in height; bays and shallows where then sucked empty. About 10 minutes later, a large return wave 2 m high crashed through the shallow bay, tearing sunken logs and debris from the bay floor and hurling the debris on to the beach and into the forest surrounding the bay. Boats and floating wharves were ripped from their moorings. A log jam at the head of Troitsa River was also dislodged and sent down the river.

Fan-Delta Development

Fan-deltas have developed over thousands of years, commencing with the high-energy, sediment-laden meltwater during deglaciation of fjord-side drainage basins.



River floods supply sediment and in the case of the Troitsa delta resulted in the aggradation of sediments over the delta through multiple distributary channels.

Although occurring under water, the presence of crescent-shaped slide scarps and blocky debris ridges on the face of a fan-delta suggests the occurrence of retrogressive rotational type of landslide movement.

Evidence of a historic landslide

Imbedded in the head scarp is a row of trees all protruding at the same level perpendicular to the scarp.

New trees fallen in the water from the erosion created by the backwash are similarly placed, suggesting the imbedded trees are from a landslide-triggered tsunami.

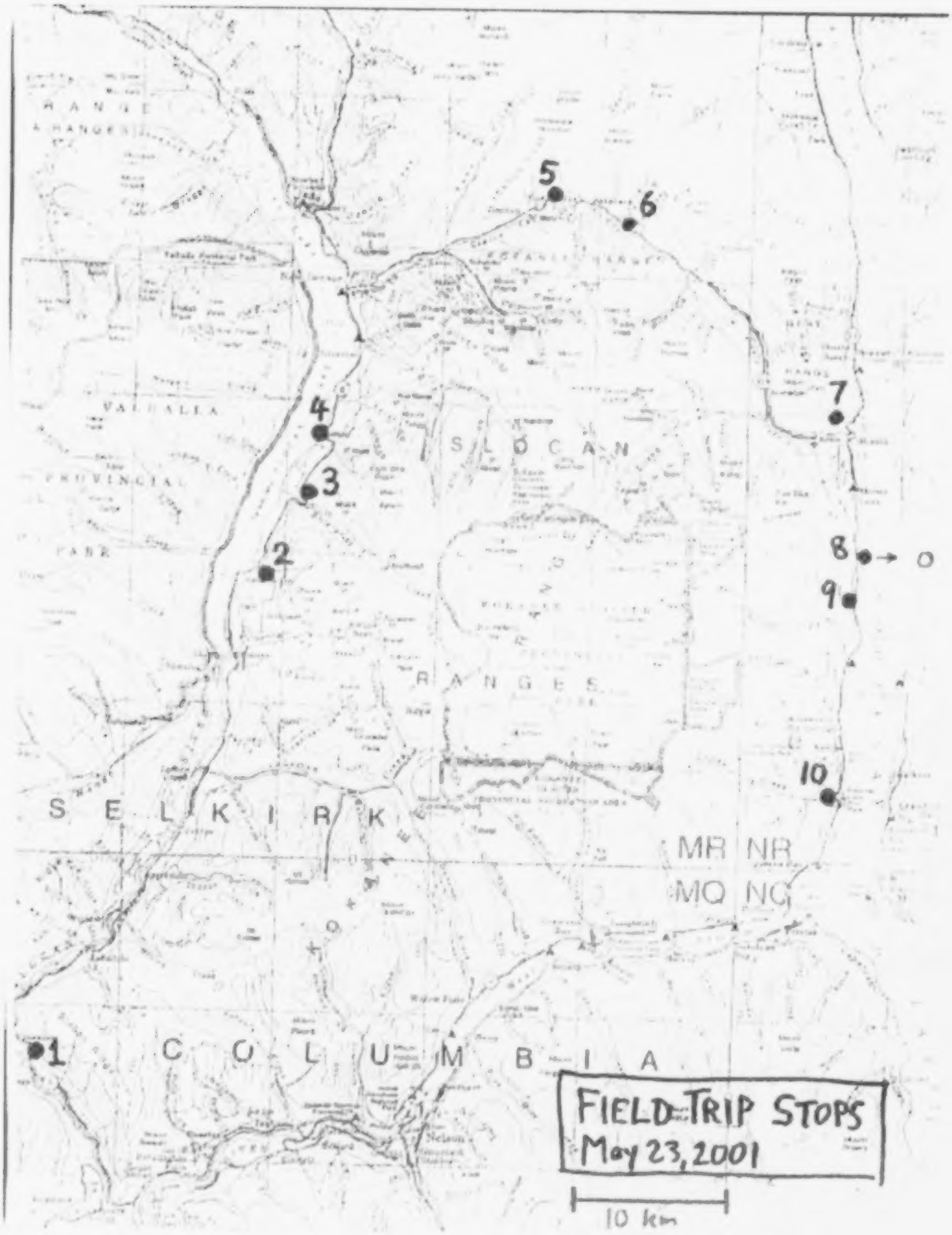
Radio carbon dating provided a possible date of 650 years B.P. since the last landslide-triggered tsunami on Trotisa Lake.

Terrain Stability and Forest Management in the Interior of B.C.

Nelson, B.C., May 23-25, 2001

Field Trip "A", Slocan Lake – Kootenay Lake

Prepared by Peter Jordan, Ministry of Forests, Nelson
with contributions from Carol Wallace and Marc Deschenes


5
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o
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10
1
VALHALLA
PROVINCIAL
PARK
SLOCAN
RANGES
SELKIRK
COLUMBIA
MR NR
MQ NG
Nelson
10 km

FIELD TRIP STOPS
May 23, 2001

5
6
7
4
3
2
8
9
10
SELKIRK
1
COLUMBIA

FIELD TRIP STOPS
May 23, 2001

Stop 1
Passmore slide

On April 13, 2000, this slump failed catastrophically, sending about 75,000 m^3 of debris across the highway and into the Slocan River. In the days leading up to the failure, the slide had been creeping slowly onto the highway. Because highways crews were doing work on the site, traffic was controlled by flagpersons at the time, so no vehicles were hit by the slide and there were no injuries. The highway was closed for several days, cutting off the Slocan Valley from Nelson and Castlegar except by a lengthy detour through Kaslo.

Photos of the slide, taken the day after it occurred, are in the appendix. More information on this site can be found in the notes for Field Trip B.

In the slide scar, there are good exposures of the glaciolacustrine clay, silt, and sand which underlie much of the Slocan Valley. These deposits are subject to slumping where undercut by river bends, or where oversteepened by road cuts, as is commonly the case in such deposits in valley bottoms throughout the B.C. Interior. The slump hazard is sometimes unappreciated, as in most places the clay is concealed beneath a thick layer of sand. At this site, there is evidence of repeated ancient failures on the adjacent slopes, probably due to undercutting by the river bend. A small seasonal stream, draining from the cliffs above, disappears into colluvium and sand above the failure. Piping in the sand layers just above the silt and clay was evident in the headscarp.

The slide is on private land. There has been no recent logging on or above the slide area, and most of the drainage basin upslope consists of steep bedrock and is only sparsely forested.

Stop 2
Memphis Creek

In May, 1990, several debris flows crossed the highway in this area, damaging the highway, water intakes, a small private hydro plant, and private property. A house was narrowly missed by one of the debris flows. The events were triggered by a heavy rainstorm on a melting snowpack. The debris flows originated in steep slopes and gullies, lying below a gentle plateau which had been heavily logged in the 1970s. The roads and skid trails had not been deactivated, which was the common practice at the time. This is an example of the "gentle-over-steep" situation, which is responsible for many landslides in the West Kootenays, and which presents challenges for planning forest development above populated valleys.

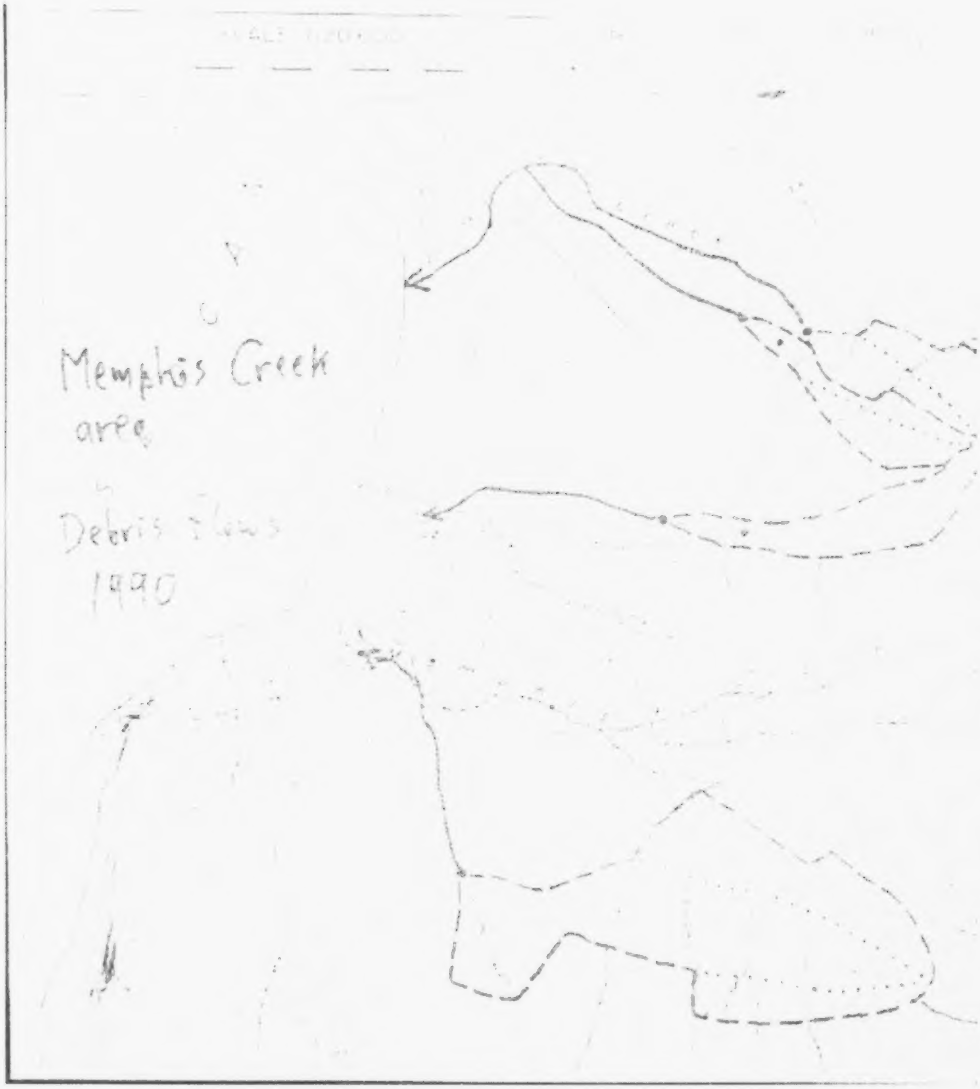
A topo map, a terrain map, and a satellite photo of the area (appendix) follow. More information can be found in the notes for Field Trip B, and in a poster at the workshop.

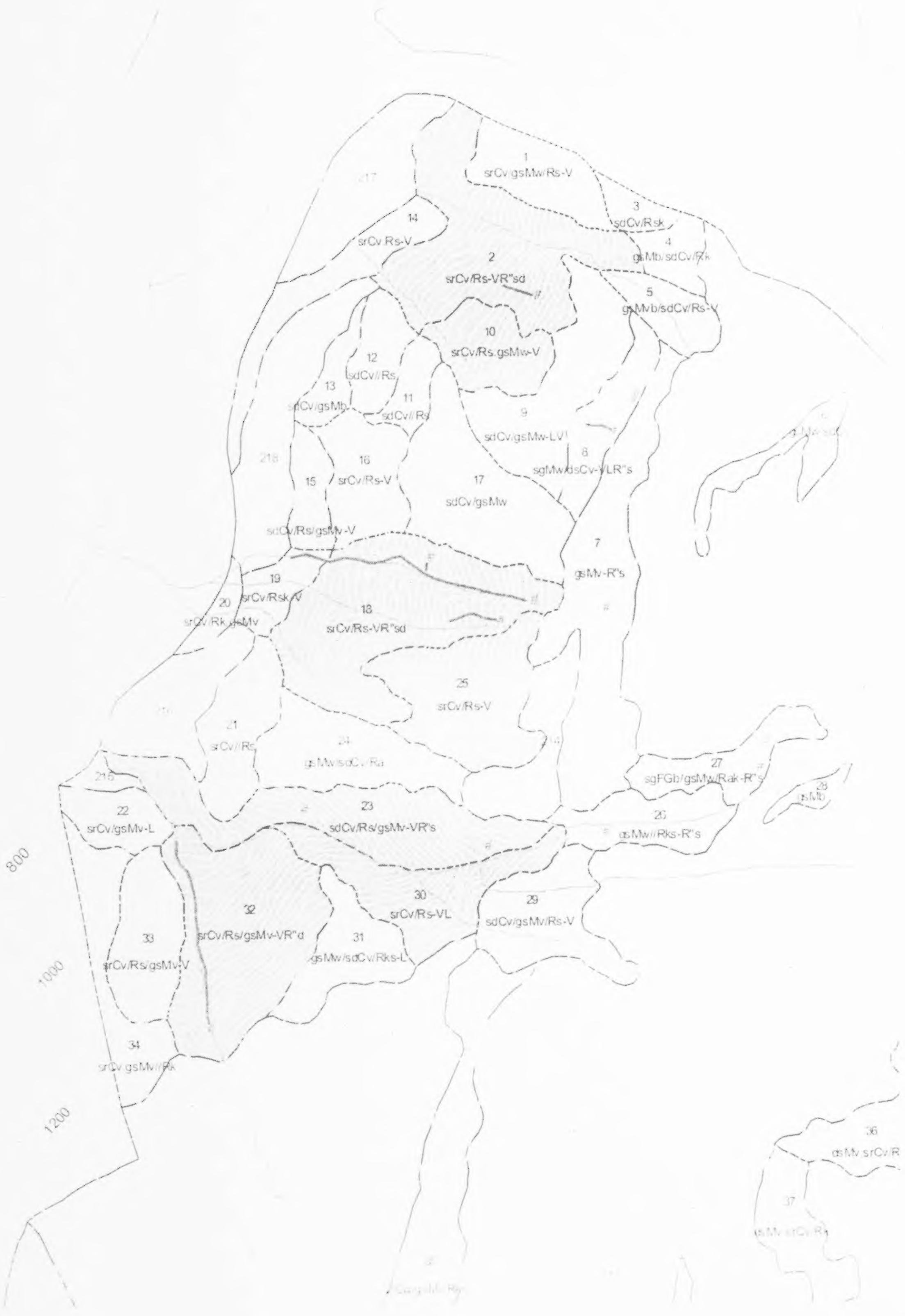
At this stop, we will look at the deposits from the largest and best preserved of the debris flows. It started in the channel of the south fork of Memphis Creek, at a break in slope where the gradient steepens to 20%, and it developed into a large debris flow as the channel steepened further downstream. It was apparently triggered by high peak discharge in the channel, not by a landslide into the channel. Roads and skid trails had captured runoff and increased the drainage area of the creek, probably substantially increasing the peak flow. The debris was mostly caught by the old highway, although some reached the new highway embankment, which had just been built.

Questions to ask here include:

- Is this channel subject to natural debris flows, and at what return period?
- If you were doing a channel assessment on this creek 50 or 100 years after such an event, would you recognize this as a channel subject to debris flows?
- Is the highway adequately protected from future debris flows?
- How should the risk of debris flows at sites such as this affect forest development planning for upslope areas?

Topo map following: post-development drainage divides are shown with dashed lines, and natural divides are shown with dotted lines. Landslide initiation points are marked with large dots.
Terrain map following: red = class V, orange = class IV, yellow = class III.


SCALE 1:20000
Memphis Creek area
Debris flows 1990



1
srCv/gsMw/Rs-V
217
14
srCv/Rs-V
3
sdCv/Rsk
4
gsMb/sdCv/Rk
2
srCv/Rs-VR"sd
5
gsMvb/sdCv/Rs-V
10
srCv/Rs.gsMw-V
12
sdCv//Rs
13
sdCv/gsMb
11
sdCv//Rs
9
sdCv/gsMw-LV
8
sgMw/dsCv-VLR"s
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gsMw/sdCv/Ra
600
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27
sgFGb/gsMw/Rak-R"s
28
gsMb
216
22
srCv/gsMv-L
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sdCv/Rs/gsMv-VR's
26
gsMw//Rks-R"s
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srCv/Rs-VL
29
sdCv/gsMv/Rs-V
32
srCv/Rs/gsMv-VR"d
33
srCv/Rs/gsMv-V
31
gsMw/sdCv/Rks-L
1000
34
srCv/gsMv//Rk
1200
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gsMv/srCv/R
37
gsMv/srCv/R

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srCv/Rs-V
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20
srCv/Rs/gsMv-VR"s
22
srCv/gsMv-L
32
srCv/Rs/gsMv-LR"d
33
srCv/Rs/gsMv-V
30
srCv/Rs-VL
31
25
34

Stop 3
Enterprise Creek

From this stop, we can view a steep slope above Highway 6 which has been recently clearcut. The logging is on private land, and is therefore not subject to the Forest Practices Code or to regulation of any kind. There has been concern expressed that snow avalanches originating in the clearcut may present a risk to the highway. There is also some slope stability risk, due to earlier logging on the less steep lower slopes which left many skid trails.

At this site, we will discuss the problems of forest development in steep terrain which is subject to snow avalanche hazards. Snow avalanches are not mentioned in the Forest Practices Code, so planning for avalanche risks often does not take place. In the case of Crown forest bordering highways, there is a protocol agreement between the Ministry of Forests and the Ministry of Transportation and Highways, which requires that proposed cutting permits which meet certain criteria be referred to Highways.

Stop 4
Silverton Lookout

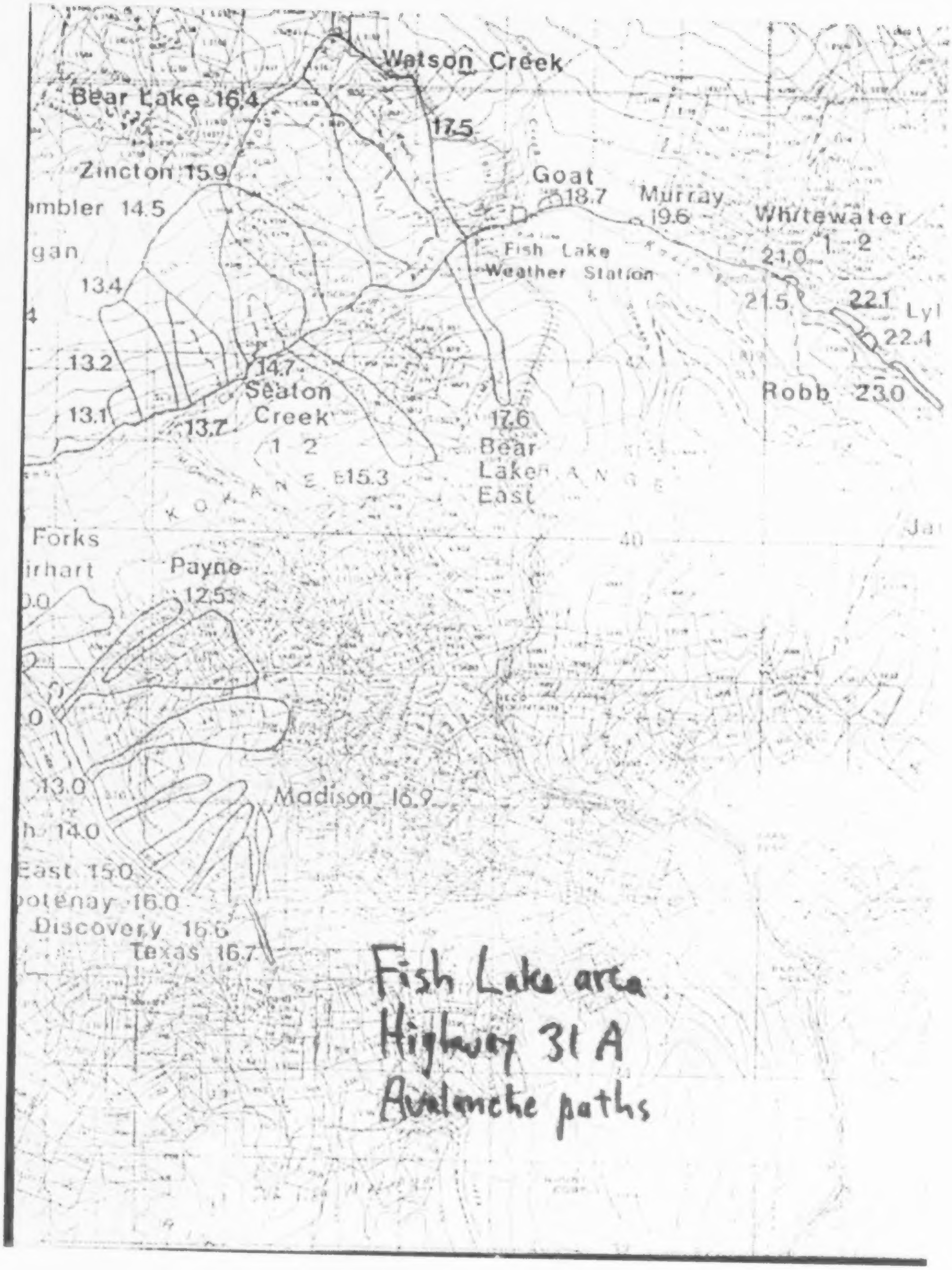
The purpose of this stop is to view a large landslide which occurred in 1996 across the lake, in Valhalla Provincial Park. No-one has done an on-the-ground investigation of this slide. From the air, it appears to have occurred in deep glacial till, which at this point is overlain by large, blocky colluvium from a failing bedrock slope above.

Stop 5
Fish Lake: New Denver - Kaslo Summit

In this area, several large avalanche paths reach the highway, and avalanche control is necessary in winter to protect the highway. Most of the avalanches originate in unforested, subalpine bowls on south-facing slopes. However, the north-facing slopes above the highway are heavily forested, and are likely to be logged in the future.

At this site, we will again discuss issues related to forest development in steep terrain which is subject to snow avalanche hazards. Questions to ask here include:

- How does the risk to valley bottom resources, such as the highway, affect forest planning? Does the Forest Practices Code adequately deal with risk?
- Can forest development take place on slopes such as these?
- What harvesting and silvicultural systems can be employed here to reduce or eliminate avalanche risk to the highway?
- What mapping, planning, and assessment strategies can be used to address avalanche hazard and risk, and how can they be included in the present forest development planning process?


Watson Creek
Bear Lake 16.4
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Fish Lake Weather Station
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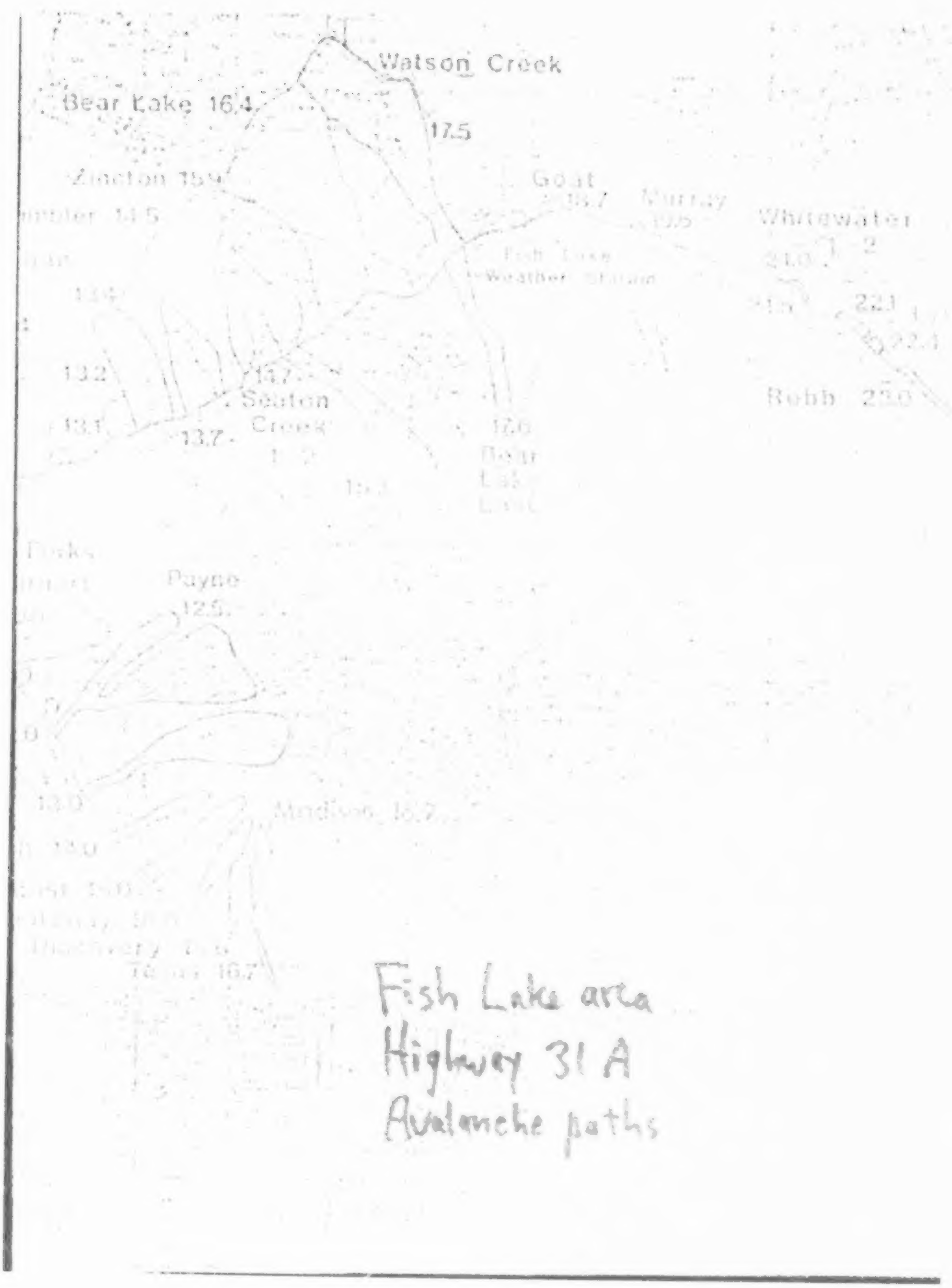
East 15.0
otenay 16.0
Discovery 16.6
Texas 16.7

Fish Lake area
Highway 31 A
Avalanche paths


Watson Creek
Bear Lake 16.4
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Zincton 15.9
Goat
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Murray
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Whitewater
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Robb 23.0
Fish Lake
Weather Station
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Creek
13.1
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Bear
Lake
East
Payne
12.5
13.0
Madison 16.7
16.7

Fish Lake area
Highway 31 A
Avalanche paths

Stop 6
Retallack bedrock slumps

This is the first of several stops looking at deep-seated, slow-moving, bedrock slump features. An important issue in terrain stability mapping and assessment is how to deal with such features:

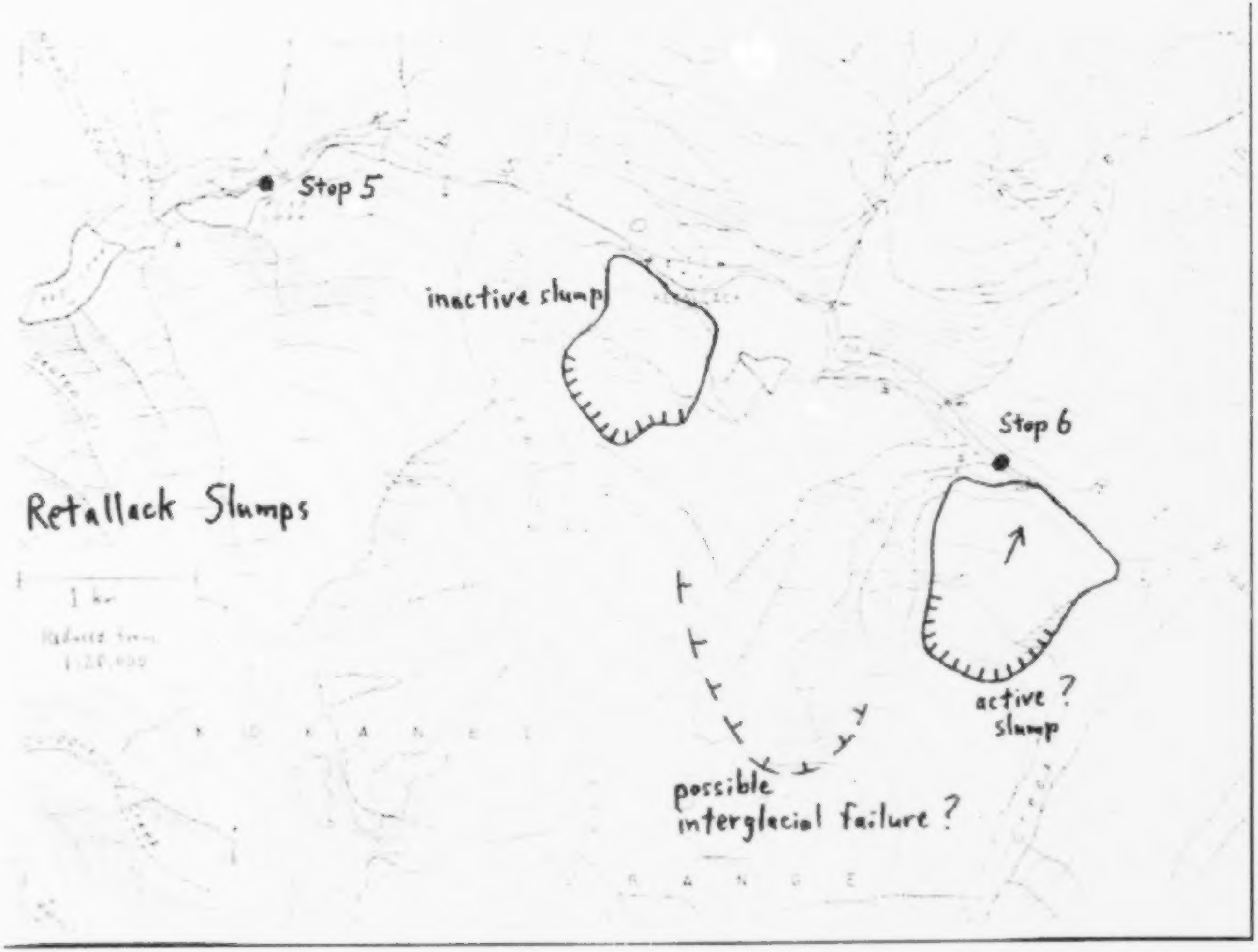
- Are they class III, IV, or V? (i.e. does class V refer only to rapid, shallow, mass movement, or to all slope instability?)
- How fast does such a feature have to be moving to be considered active?
- What are the implications of such failures for forest development planning?
- Can increased snow accumulation and melt due to clearcutting on and upslope of these features present a risk of more rapid failure?
- What slope instability problems can be associated with road construction on these slumps?

This area is underlain by the Slocan Group, mostly fine-textured Mesozoic sedimentary rocks. In some areas, they are quite weak and are subject to slumping, especially in the Kaslo River valley where there are at least four such large slumps.

This slump appears to have had some postglacial movement, as indicated by its advance into the wide meltwater channel of the Kaslo River. A similar nearby slump does not appear to have moved since deglaciation. Some old logging is evident on and above the slide, mostly on private land.

There has been extensive mining activity in this area. Many claims are from the 19th century and are freehold title. Now, with reduced interest in mining, claims are bought and sold for their timber values, and most are heavily logged with little or no regard for modern forest practices or environmental impacts. The Kaslo River is a watershed supplying the town of Kaslo*. In the upper reaches of the river, extensive aggradation and channel instability is evident. This may be partly due to mining and logging activity over the last 110 years, and partly due to a large forest fire in the early 20th century.

* Kaslo's community watershed is a tributary of the Kaslo River. The town also has a license on the Kaslo River itself but does not use it as its primary source of water.


Stop 5
inactive slump
Stop 6
Retallack Slumps
1 km
Reduced from
1:20,000
KOKANEE
active ? slump
possible interglacial failure ?
RANGE

Stop 7
Kaslo - Mount Buchanan slump feature

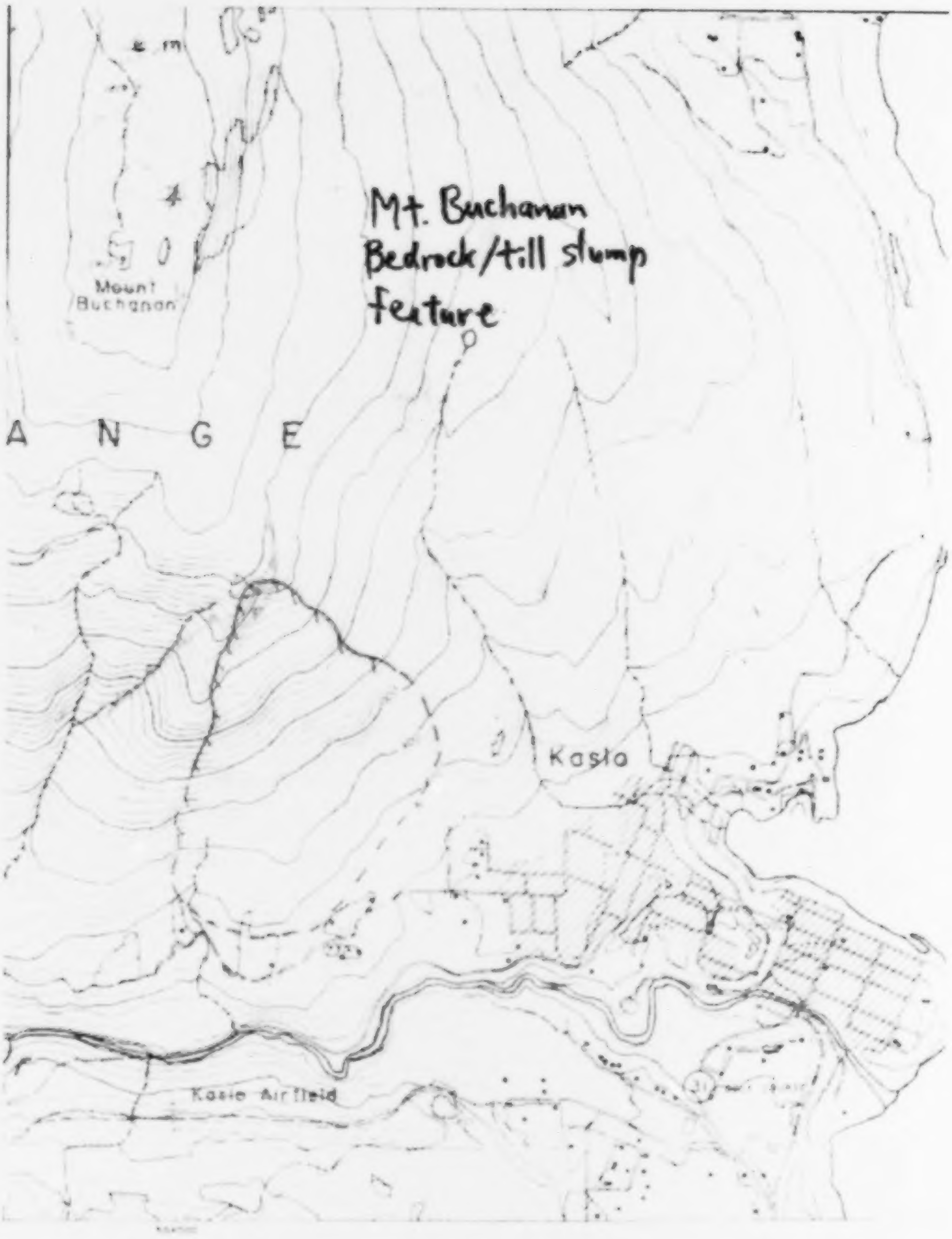
A large area of the slope of Mt Buchanan, immediately above the town of Kaslo, appears to be undergoing slow-moving slumping or creep. Although there has been a town here for 110 years, and some small-scale slope instability features were undoubtedly noticed, the presence of a large possible failure went unnoticed until it was discovered only in the last few years. The boundaries of the feature are quite indistinct; rather than a single, well-defined slump, as at Retallack, it is more likely that a large disconnected area is experiencing various types of creep, slumping, and toppling.

At this stop, we will look at features at the toe of the slope, including springs which shift over time, tufa deposits, cemented colluvium, and rock lobes and grabens. All of these provide some clues to the presence of possible bedrock instability.

The area is included in the forest license of the Kaslo Community Forest Corporation, which is now preparing a Forest Development Plan for the slope. The main issue of concern here is how possible risks related to bedrock instability affect forest development planning. The area is high risk because of its immediate proximity to the town - although the hazard of a large landslide is low to very low, the consequence is very high. The likelihood of catastrophic failure, or even of more rapid movement, is probably extremely low to nonexistent. However, small debris flows which could affect private land are of greater concern, and these could be triggered by small road- or logging-related failures within the large unstable area. Water quality and quantity issues related to the springs, which have poorly defined and difficult-to-identify source areas, is also a significant concern.

From just south of Kaslo, there is a viewpoint where we can look at the entire slope. The scarp at the top of the feature is in glacial till. Apparently the failing area involves both bedrock and till. It is interesting that a major thrust fault roughly coincides with this scarp.

Kaslo lies at the centre of the Kootenay Arc, a zone of intensely deformed sedimentary and metamorphic rocks, where the accreted terranes joined ancestral North America. Four terranes are visible from here: North America, Kootenay, Slide Mountain, and Quesnellia. The fault system on Mt Buchanan marks the approximate boundary of the Paleozoic and Precambrian rocks of North America to the east, and the Mesozoic rocks of the accreted terranes to the west. Further northwest along Blue Ridge, serpentine is common in this fault system. If present here, it could contribute to deep-seated bedrock instability.


Mt. Buchanan
Bedrock/till slump
feature
Mount
Buchanan
A N G E
Kaslo
Kaslo Airfield
31

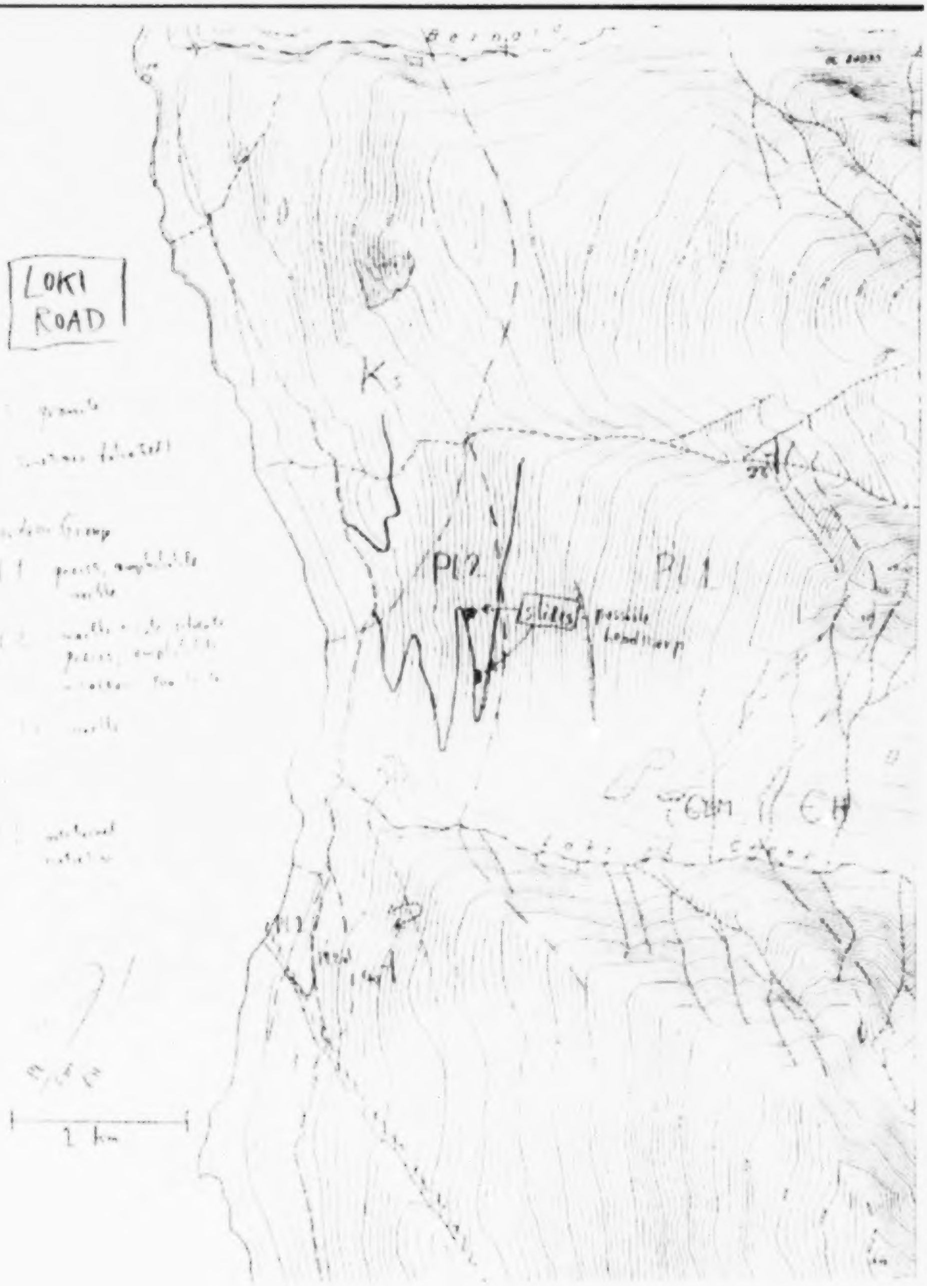
Stop 8
Fletcher Creek falls and beach, and Loki Creek landslides

It is about a 10 minute walk down to the beach at Fletcher Creek falls. From here, there is a good view across the lake to several slump or creeping bedrock slope features.

Directly across the lake is a new Forest Service road, accessing a SBFEP operating area north of Loki Creek. On construction, a zone of displaced, unstable rock was encountered, resulting in two large cut-slope failures. These are visible as openings above the road. The failures have been stabilized for the time being, and a usable although narrow road has been built; however, the long-term future of this road remains in doubt.

On field investigation, a large area of deformed rock was encountered, apparently due to creep, slump, and toppling processes similar to those on Mt Buchanan. The boundaries of the failing area are quite diffuse, and the feature was not identified by reconnaissance terrain stability mapping. In the field, several indicators of bedrock instability are noticeable, most prominently some areas of grabens, tension cracks, and huge displaced bedrock blocks; however, all these features appear to be inactive. From this viewpoint, an escarpment which probably outlines the top of the failing area is visible.

The slope is underlain by the Lardeau Group, Paleozoic metasedimentary rocks which are subject to a high incidence of bedrock landslides. They dip to the west at about 40 degrees, somewhat steeper than the slope, although because the orientation of the bedding is irregular, there are probably places where the bedding parallels the slope. The next two mountain faces to the south also have bedrock instability. The southern feature is a very large, well-defined, bedrock landslide in the watershed of Indian Creek, above the town of Riondel.



LOKI ROAD
K: granite
PL1 gneiss, amphibolite, marble
PL2 marble
K
PL2
PL1
slides
possible headscarp
GM
CH
1 km

Stop 9
Woodbury-Fletcher Road and landslides

The lower part of this Forest Service road, on a steep slope above Highway 31, has been the site of several landslides. It was originally a private road, used for logging. The largest slide here occurred in 1992, when it was still privately owned. The following year, the Ministry of Forests purchased the road to access a development area above. Since then, the Ministry has done considerable work upgrading the road to improve its stability. However, several landslides have originated on skid trails from the steep logged slopes above the road, which are still privately owned. Most of these stopped on the logging road; however, one reached the highway.

Like most roads of its era, this was built the cheapest possible way, using a bulldozer and cut-and-fill construction. In some places, road fill is supported by stumps and logs on very steep slopes. Part of it, in the vicinity of the large slide, have been reconstructed. For most of its length, landslide prevention is based on drainage control, and keeping water off the unstable fills. The site is high risk due to the proximity of the highway. It illustrates the problems, common in the interior, of old substandard roads, and of landslide hazard due to poor logging and engineering practices on private land.

Stop 10
Coffee Creek

In November 1999, a very unusual fall rainstorm caused a debris flood on Coffee Creek. The highway bridge miraculously survived, but a large part of the highway bordering the creek was washed out. Many landslides occurred in the drainage, some from old logging and from roads; these contributed substantial debris to the creek. The Forest Service road paralleling the creek was washed out in numerous locations, and will not be rebuilt.

More information on this event is given in a poster at the workshop.

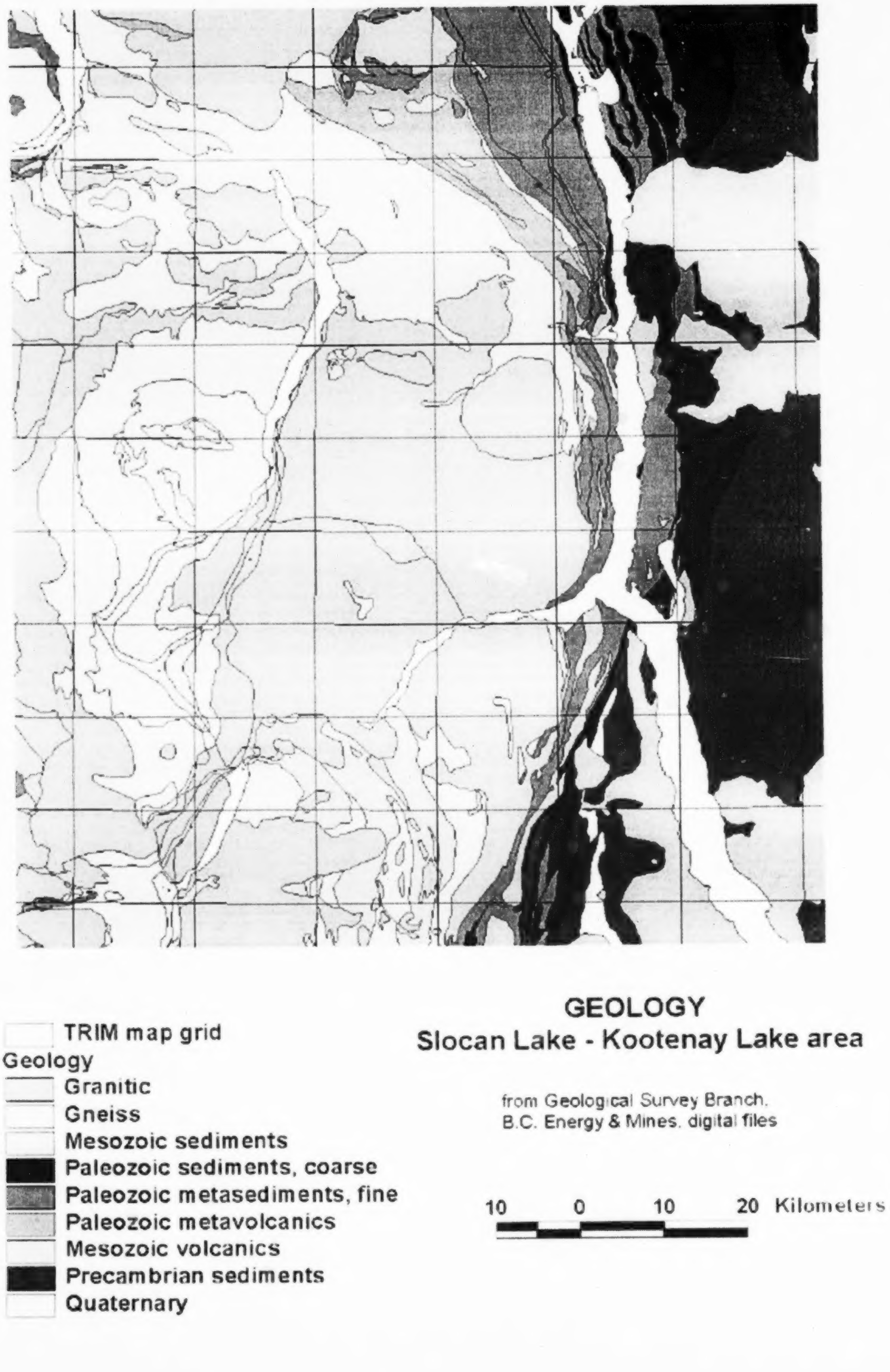
Appendix

Geology map

Satellite image

Relief map generated from TRIM grid

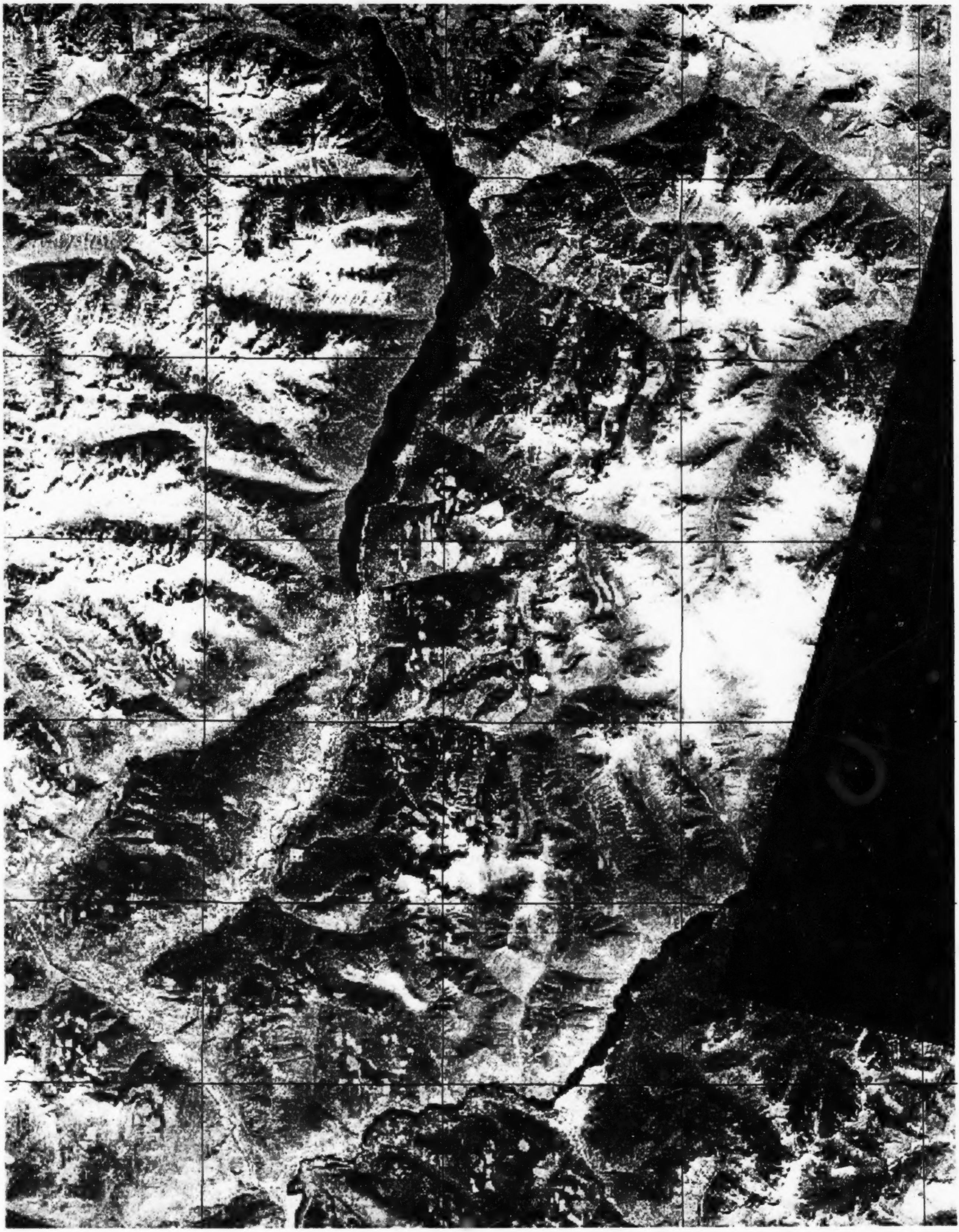
Photos for stops 1, 2, 3, 6, 7, 8



TRIM map grid
Geology
Granitic
Gneiss
Mesozoic sediments
Paleozoic sediments, coarse
Paleozoic metasediments, fine
Paleozoic metavolcanics
Mesozoic volcanics
Precambrian sediments
Quaternary
10
0
10
20
Kilometers

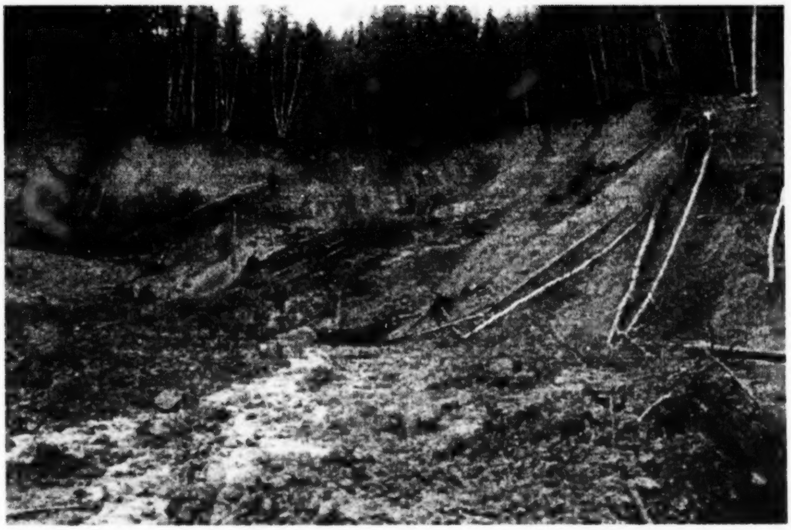
GEOLOGY
Slocan Lake - Kootenay Lake area

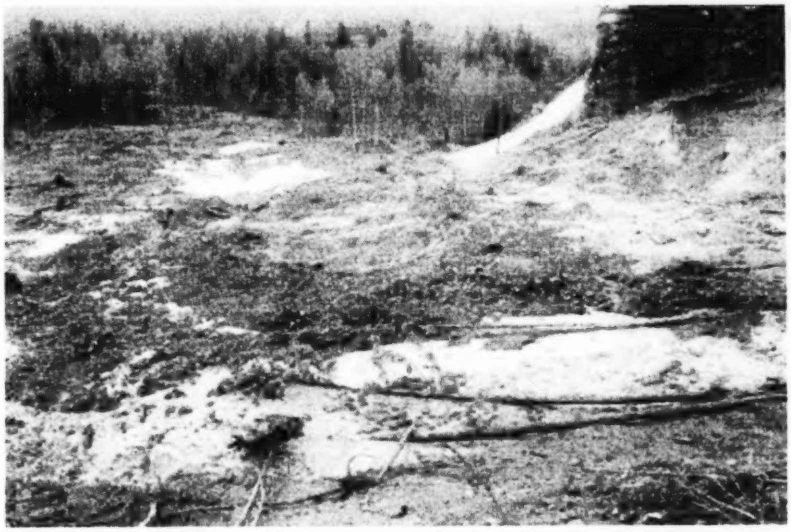
from Geological Survey Branch,
B.C. Energy & Mines, digital files

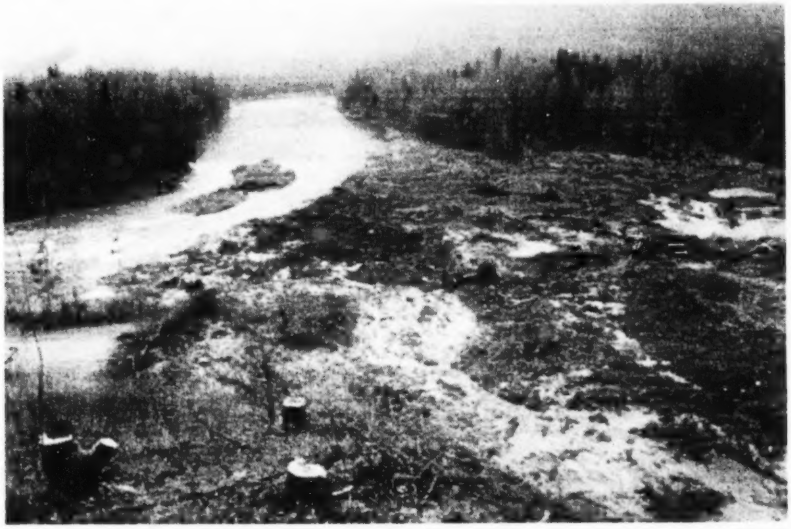


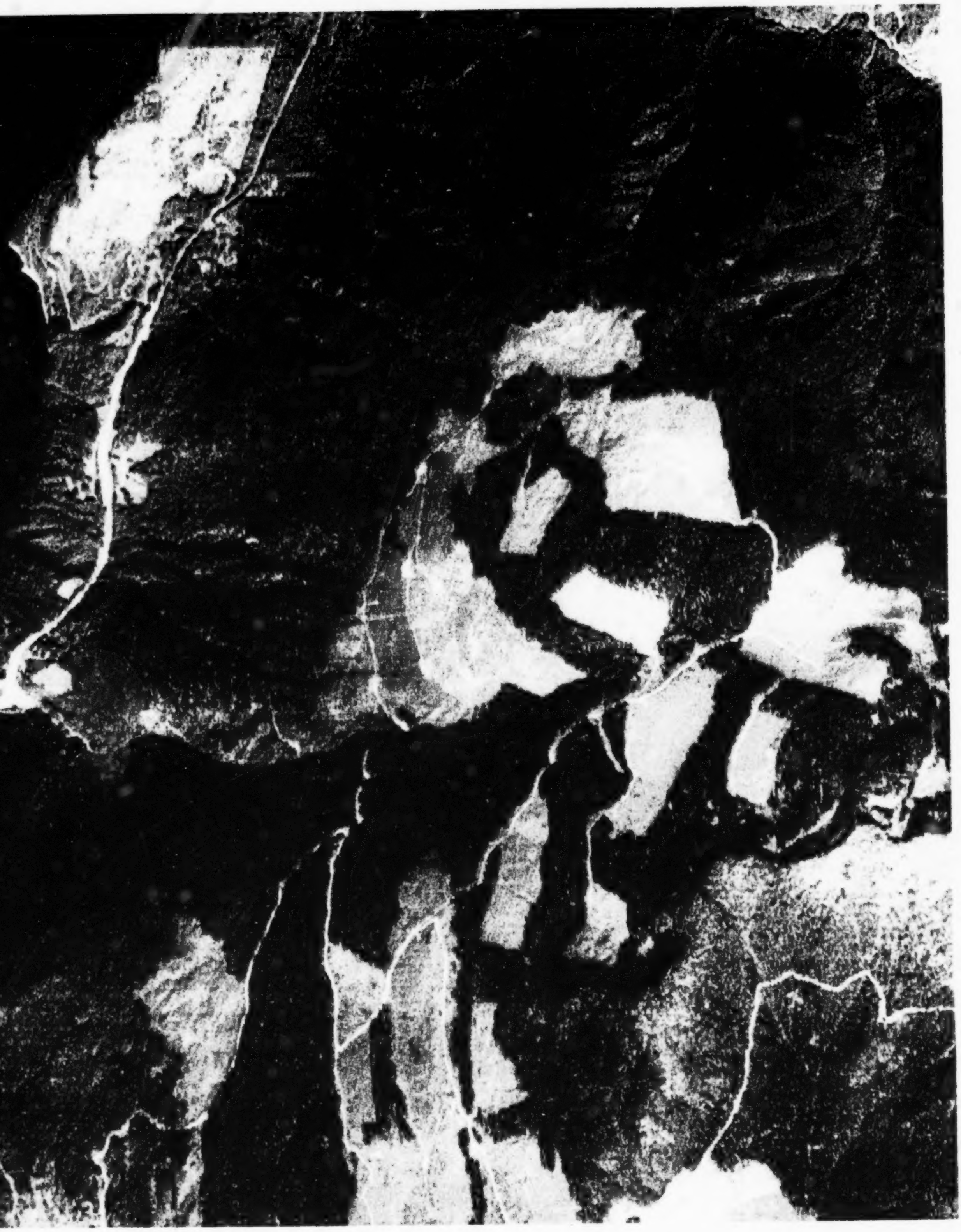
Stop 1: Passmore slide
April 13, 2000

Three photos showing headscarp, central portion, and runout across Slocan River.





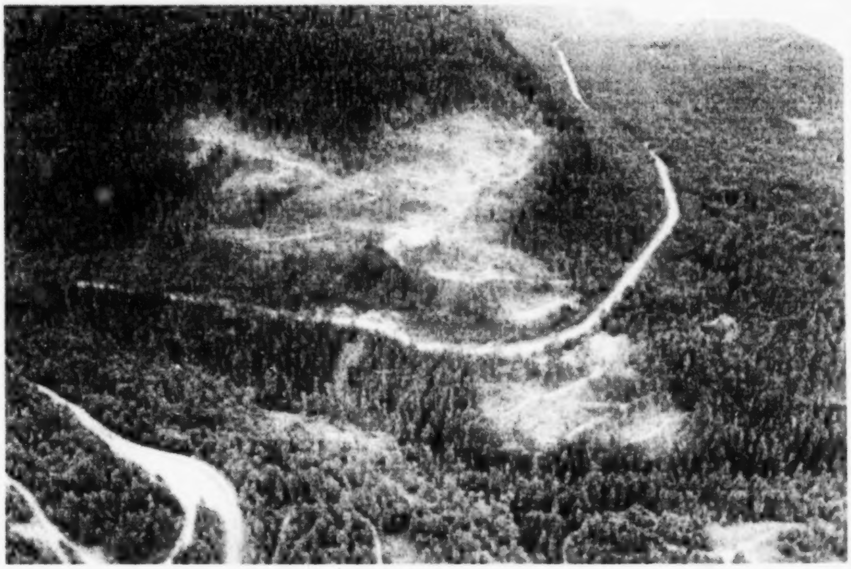


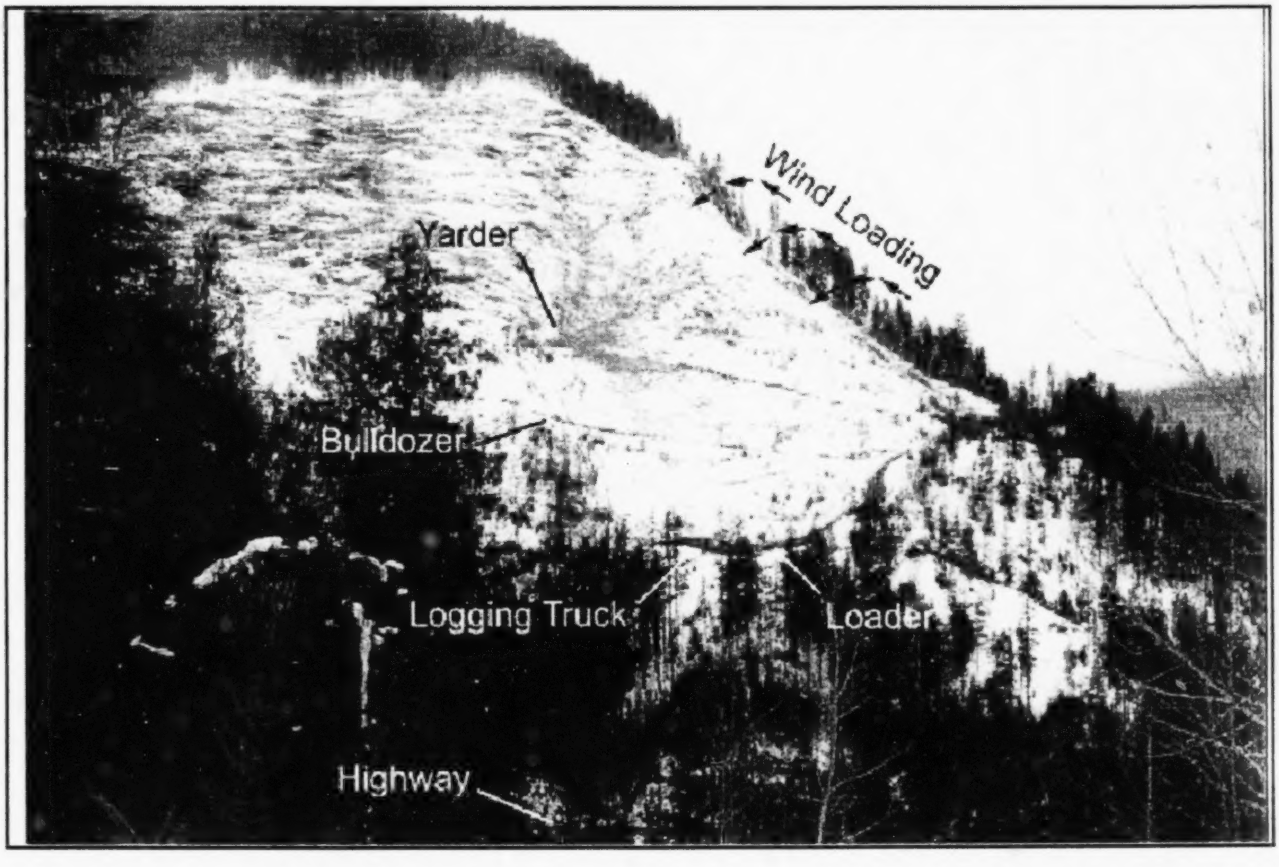


2 Memphis Creek Satellite photo showing approximately the same area covered by the map.

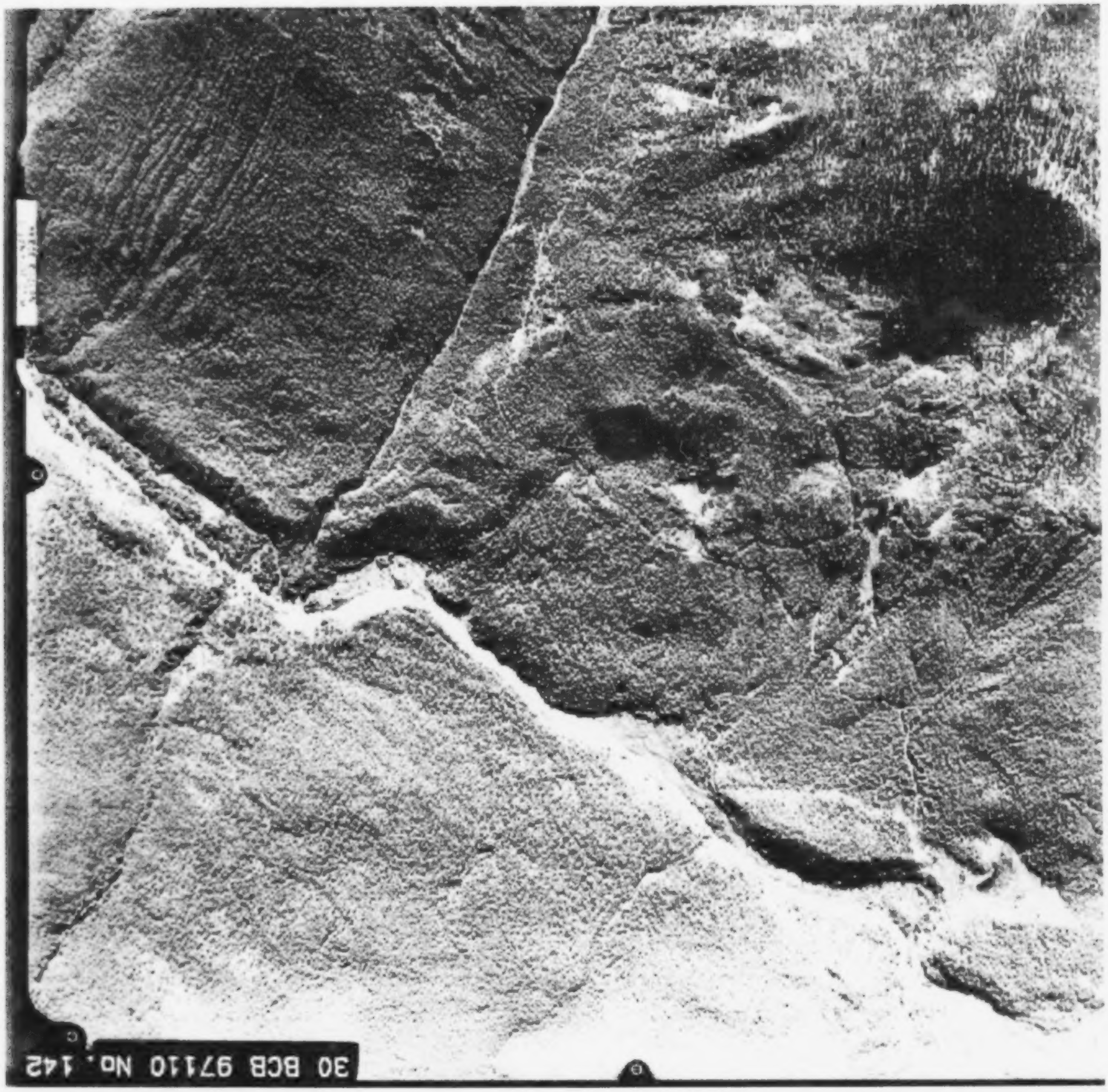
Stop 3
Enterprise Creek

1. Slope above highway before logging the recent clearcut. Skid trails from private land logging continue to present a slope stability hazard to the highway.




Wind Loading
Yarder
Bulldozer
Logging Truck
Loader
Highway

2. Photo of recent clearcut taken during logging, showing features related to avalanche hazard. This photo is taken from P. Weir, "Management of Snow Avalanche Prone Forest Terrain" (draft, in press).

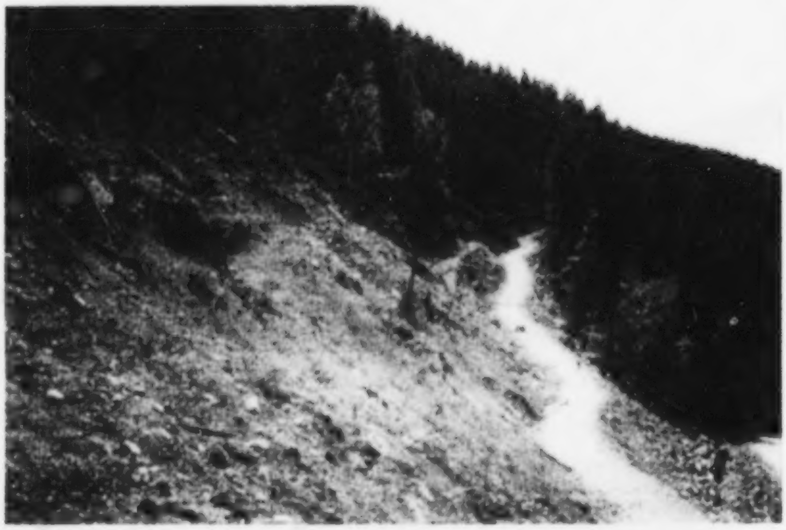

30 BCB 97110 No. 142

Stop 6. Retallack rock slump. Note apparent postglacial movement of slump into Kaslo River glacial meltwater channel.

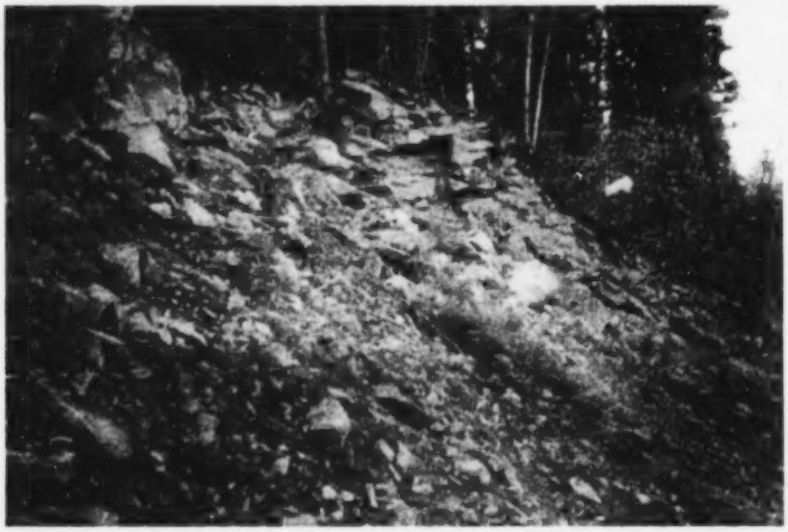
Stop 7. Kaslo rock slump - several views showing outline of feature.

Stop 8.
Loki Road failing bedrock slope (across lake)

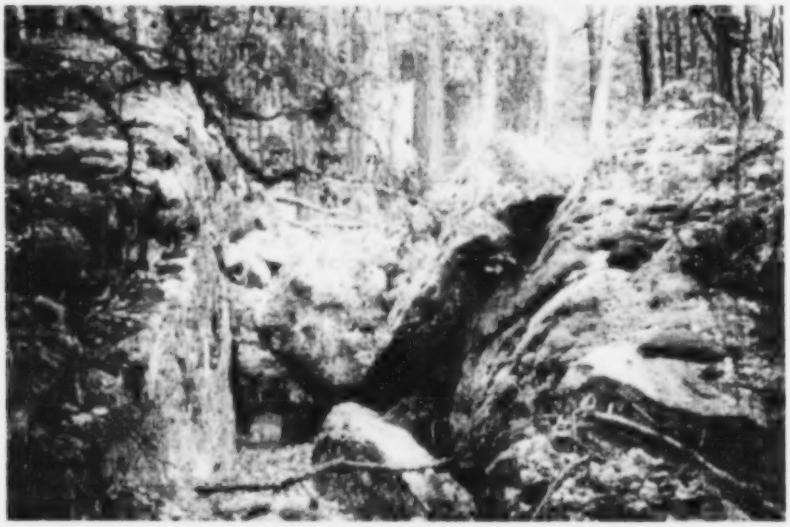
1. Cut failure above switchback.



2. Smaller cut failure near second switchback. Displaced bedrock blocks appear to overlie till.



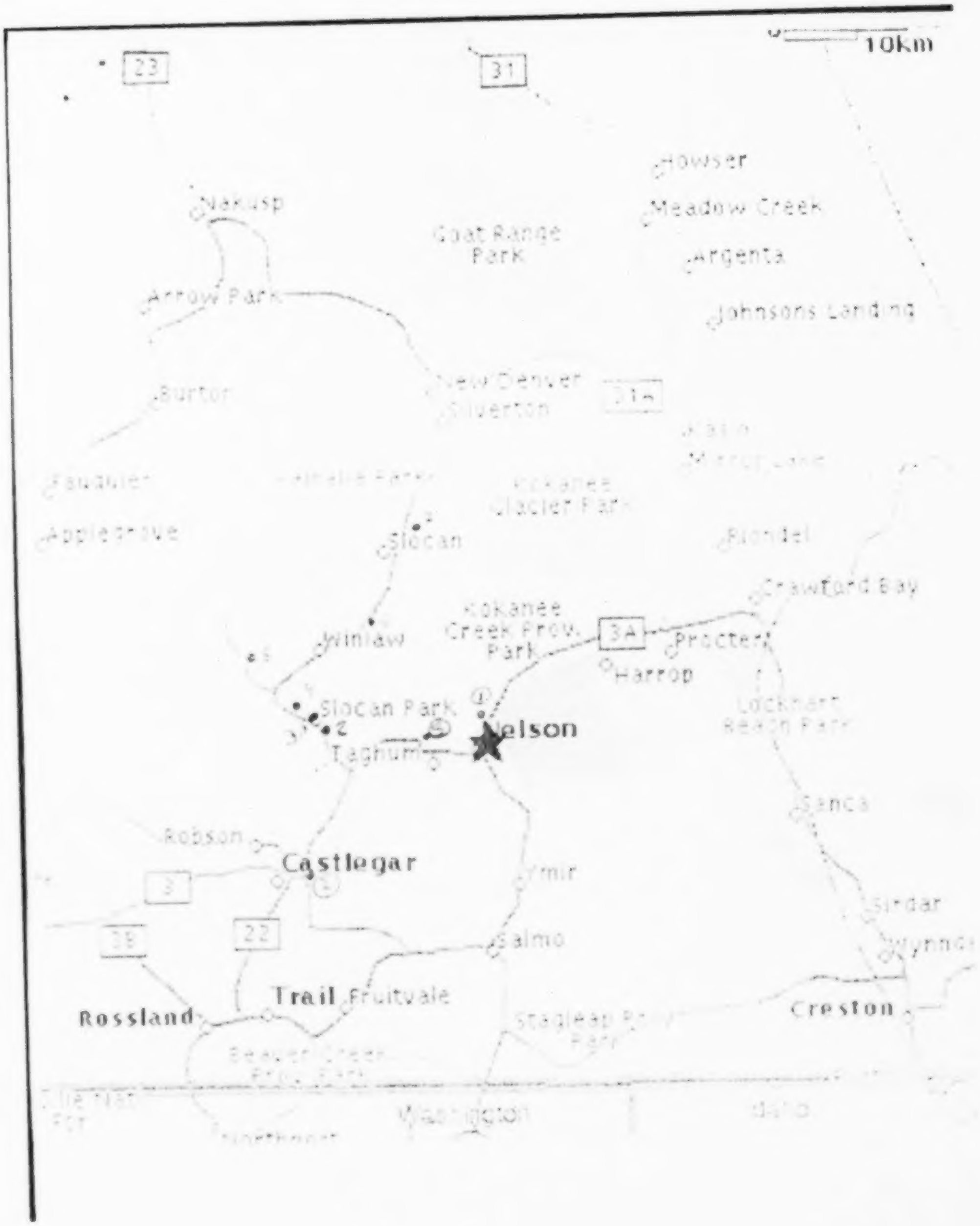
3. Grabens in failing slope above road.



Terrain Stability and Forest Management in the Interior of BC
Workshop – Nelson, BC
May 23rd – May 25th
Field Trip B – May 23rd

Prepared by: Dwain Boyer, Doug Nicol, and Nichole Boultbee

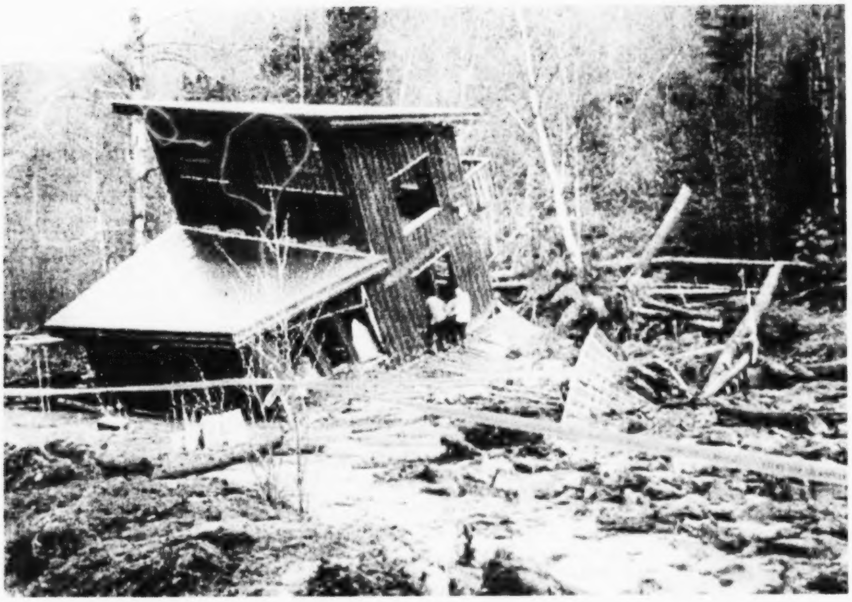
8:15 am	**Depart from Prestige**
8:45 am	**D.L. 10027**
9:15 am	**Slocan Park Slide**
10:00 am	**Passmore Slide**
11:30 am	**Little Slocan Slide**
12:45 pm	**Appledale Slide and Lunch**
2:45 pm	**Memphis Creek**
4:00 pm	**Smallwood Creek Slide**
5:00 pm	**If time – BNR Landslide**

0 10km
23
31
Nakusp
Goat Range Park
Howser
Meadow Creek
Argenta
Johnsons Landing
Arrow Park
New Denver
Silverton
31A
Burton
Kaslo
Mirror Lake
Fauquier
Valhalla Park
Kokanee Glacier Park
Applegrove
2
Slocan
Riondel
Crawford Bay
Kokanee Creek Prov. Park
3A
Procter
Winlaw
Harrop
6
4
Slocan Park
5
2
3
Nelson
Taghum
Lockhart Beach Park
Sanca
Robson
Castlegar
3
Ymir
Sirdar
3B
22
Salmo
Wynndel
Trail
Fruitvale
Rossland
Stagleap Prov. Park
Creston
Beaver Creek Prov. Park
Washington
Idaho

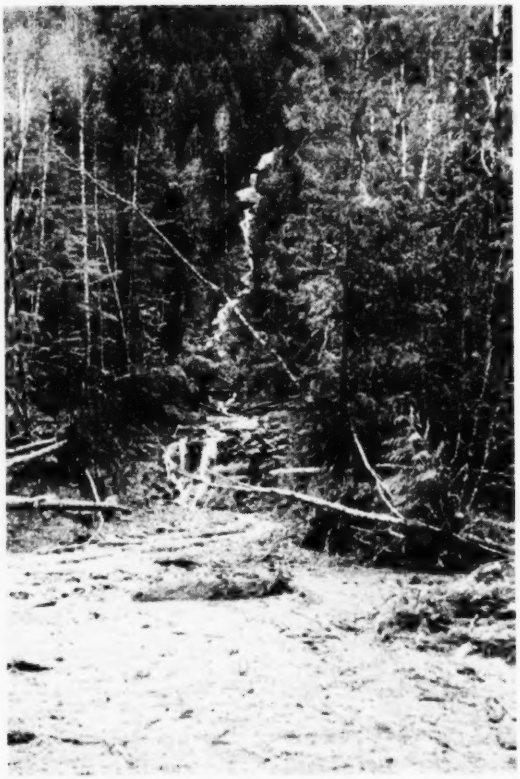
SLOCAN PARK SLIDE

APRIL 23, 1996

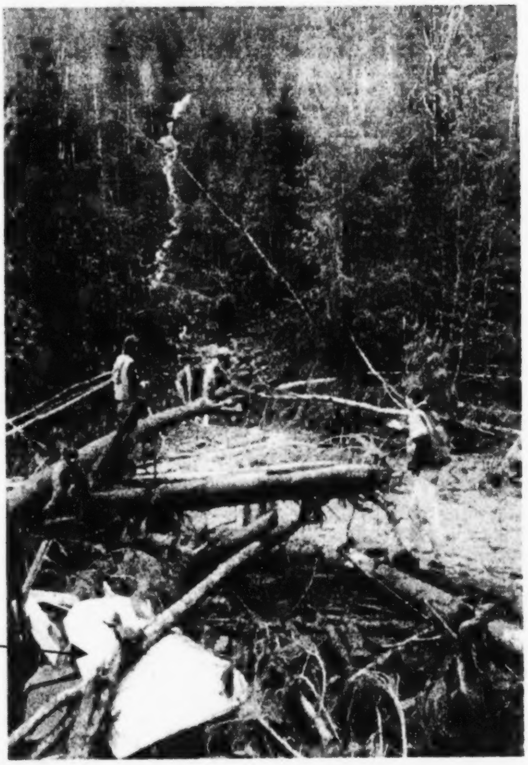
Slocan Park Slide



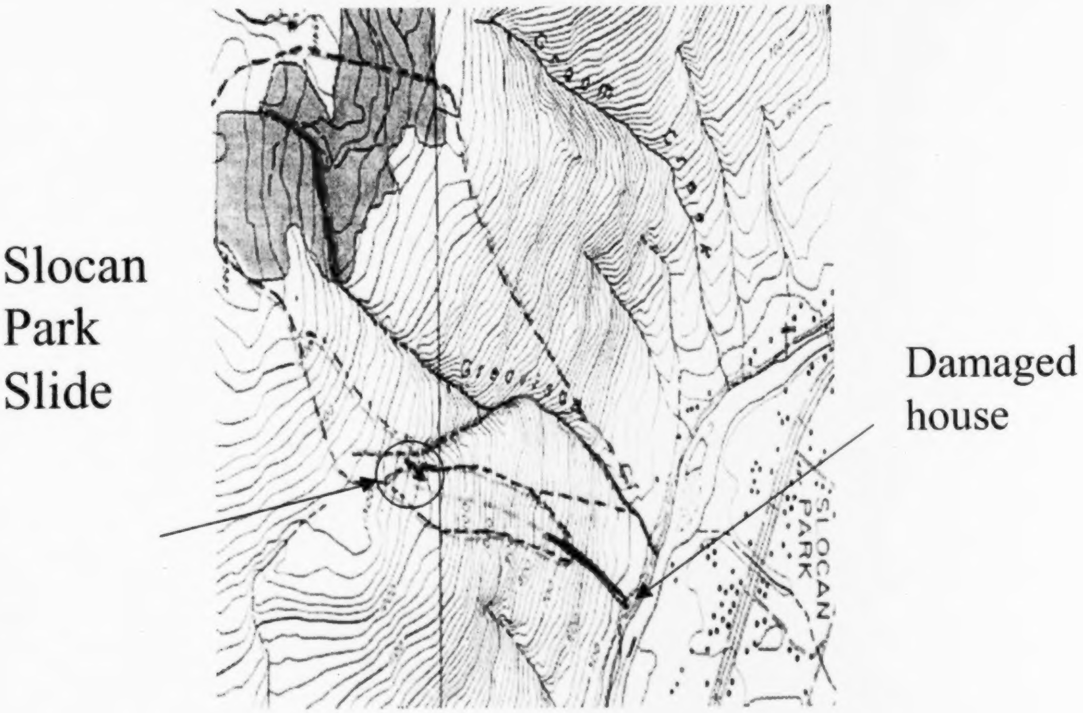
Slocan Park Slide April 23,



Slocan Park



Two vehicles



Destruction caused by clearcut, McCrory

By JOLANDA WASKITO

The mud slide that destroyed a Slocan Park home last week was the result of clearcutting in the area, two environmental groups charge.

"There are huge clearcuts along the top of the ridge with a snowpack of one metre still melting," Valhalla Society director Colleen McCrory said.

"Although the mud slide didn't start at the clearcut, the heavy runoff may have contributed."

A team of Valhalla Society and Silva Forest Foundation foresters surveyed the area above the slide and are now calling for an independent hydrological investigation into the cause of the slide.

After reviewing the field team's observations, Herb Hammond of Silva said that clearcutting drastically reduces the capacity of the forest floor to act as a sponge.

"Combined with rapid snow melting, this factor results in overloading streams during runoff periods — There is evidence this may have happened on the day of the mud slide," Hammond said.

Craig Pettitt, a former forest technician who worked for the Forest Service for 15 years, surveyed the area with Jody and Ed Hoffman of the Silva Foundation.

"There are already expert hydrology reports that warn us of some more mud slides if clearcutting and road-building goes ahead in the valley's watersheds," Pettitt said.

Studies have shown that spring runoff from clearcuts can be up to ten times greater than in uncut forest, and soil movement during that period can be 10 to 100 times greater than in forested areas, he added.

The Ministries of Transportation and Environment had their field team — geotechnician engineer Roy Lidgren and Dwayne Boyer of the Water Management Branch — check the area by helicopter the morning after the April 23 mud slide.

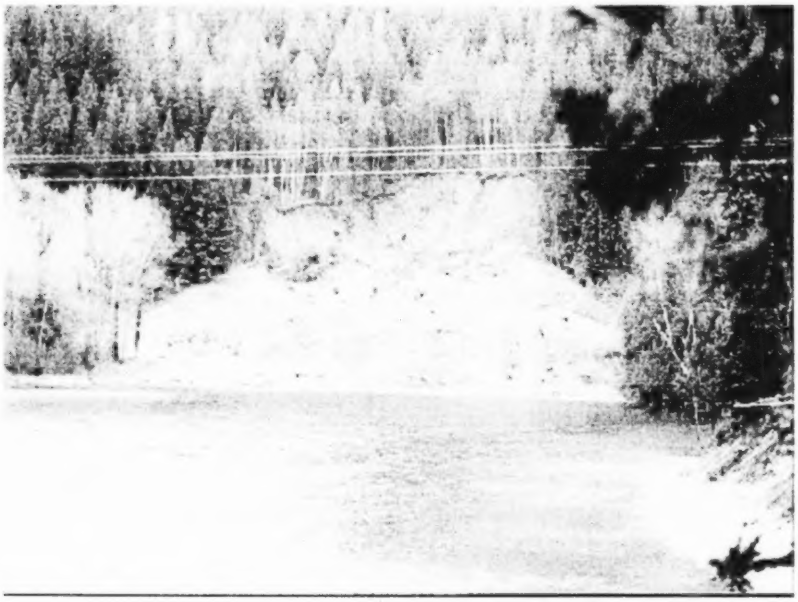
"They found that it was entirely a natural occurrence," ministry spokesperson Eliah Farrel said. "The soils are super-saturated and they couldn't hold the heavy rains anymore."

A small slide had landed into a gully 700 to 1,000 metres above the now-destroyed home, it built up and then came down in a torrent.

Slocan Park
Slide

Natural Creek
Diversion

Terrain Stability and Forest Management in the Interior of British Columbia

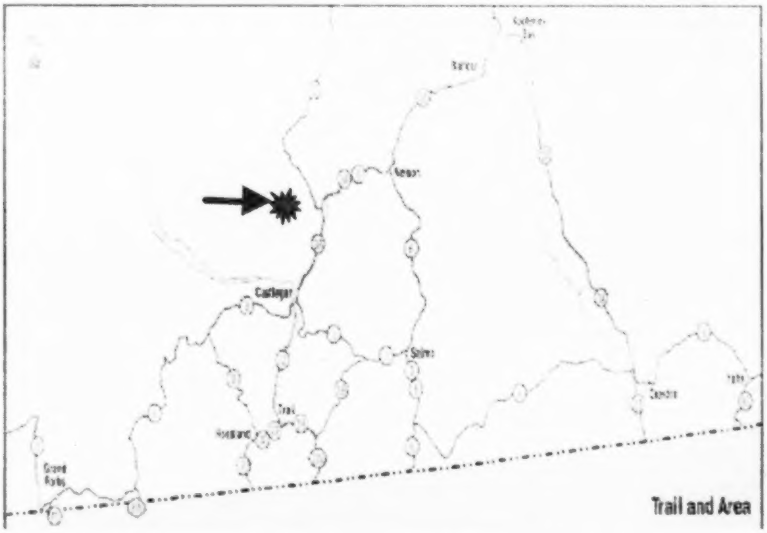


Passmore Slide Field Visit
Highway 6

M. P. Walsh, P.Eng.
Regional Geotechnical & Materials Engineer
Minstry of Transportation & Highways

History

The Passmore Slide is located on private land on the upslope side of Highway 6 approximately 20 kilometres north of the Highway 3A/Highway 6 junction (see Figure 1). Slide monitoring was first initiated in the Spring on 1994 when small slope creep movements encroached on the highway shoulder.



Passmore Slide Location Map
Figure 1

Previous to the main slide, typical slide movements were generally 1 to 2 metres of slow creeping movement over a two month timeframe during mid-spring. The movements were mostly confined to the toe of the slide at the highway shoulder and no movement of the highway was observed. (se Figure 2). The overall slide comprised of several slump blocks extending approximately 70 metres upslope to the present backscarp.

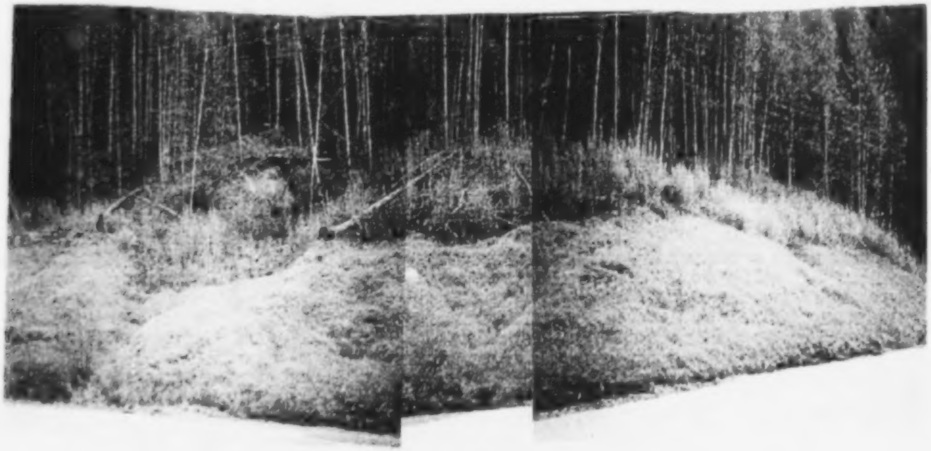
Given the nature of the slide and the location on private land, no mitigative measures were undertaken. An observational approach was used.

Site Investigation

A subsurface investigation and review of the local geology was performed in the fall of 1999. Two drill holes were advanced on the lower portions of the slide to determine soil types, groundwater elevations and to install groundwater monitoring and slope movement instrumentation.

The investigation revealed loose to dense sands overlying very stiff varved silts. No substantial groundwater in the sand or the silts was discovered, however, zones of surface water were observed in the slide zone.

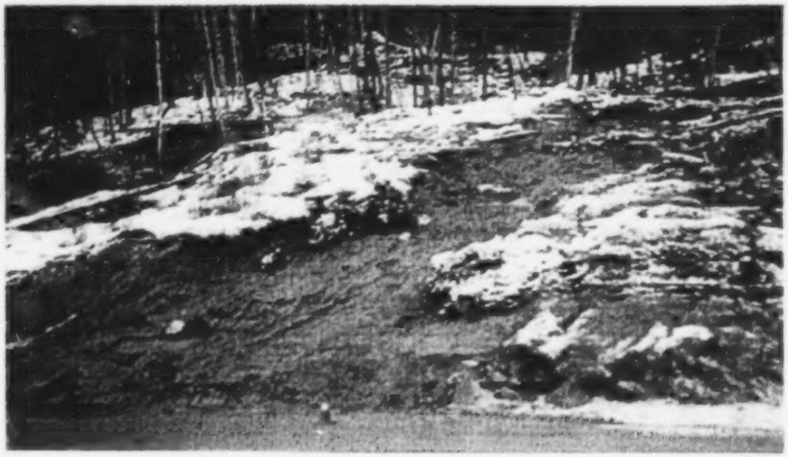
A review of the area indicated that the local groundwater was sourced by a waterfall coming off bedrock approximately 300 metres upslope of the slide. The waterfall completely infiltrated into the ground with no visible surface flows occurred downslope.



Pre-slide, typical toe movement
Figure 2

Pre - Failure

In February of 2000, a small failure at the toe of the slide occurred, depositing approximately 250 cubic metres of material on the road (see Figure 3). This was the "worst case" type of failure that was envisioned for the site.



February 2000 Surficial failure
Figure 3

Day of Failure

On April 13, 2000 larger than normally observed movements of the slide began. There was approximately 2 metres of translational movement of the toe and 3 metres vertical drop of the block at the headscarp.

Maintenance crews excavated material at the toe of the slope to maintain traffic flow through the area. Traffic was reduced to 1 lane alternating during and after the maintenance crew was on site. West Kootenay Power was informed that a power pole was involved in the slide movement and that there may be damaged if movement continues. The lines were set to not re-energize if the breaker was tripped.

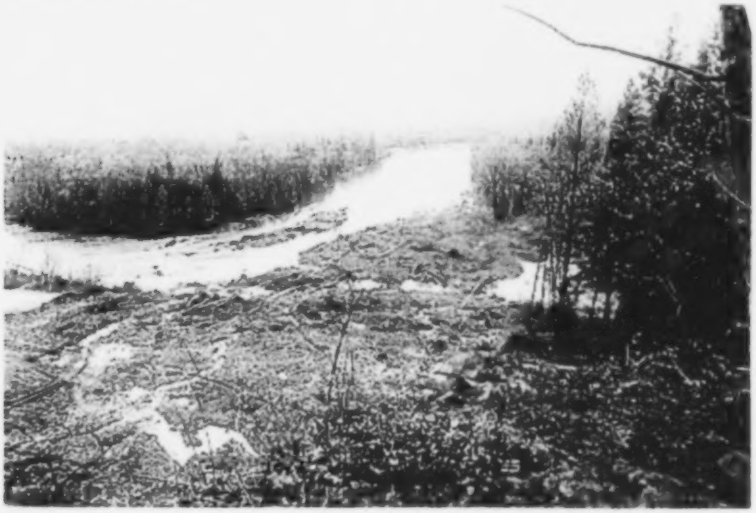
There was a noticeable increase in surficial water flow at the toe of the slide and significant bulging of the asphalt in the northbound lane at the north edge of the slide. Neither of which were observed before.

Some cracking and falling of trees was also observed during the day.

Maintenance crews left the site at 3:30pm and the traffic was left at one lane alternating with the flaggers approximately 30 metres back of the slide boundaries.

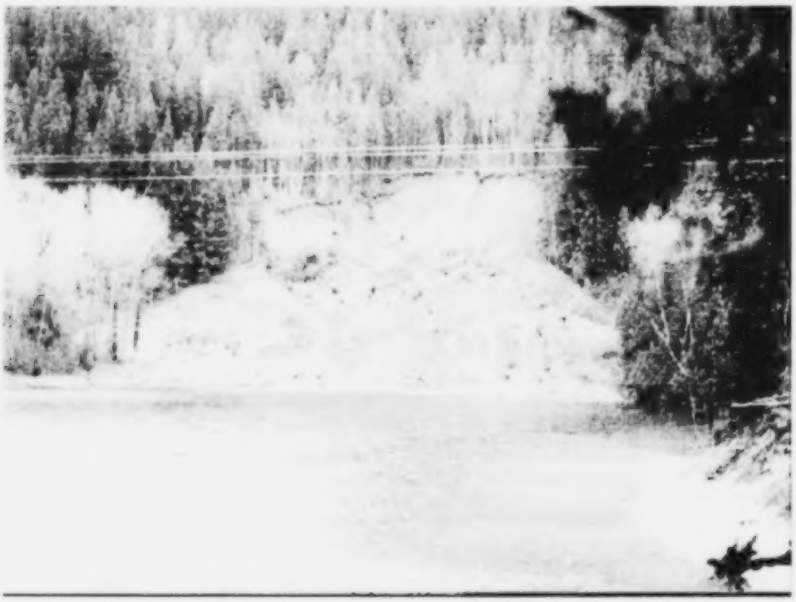
At approximately 5:15pm a 75,000 cubic metre slide catastrophically released. The debris flowed across the Slocan river and blocked the flow for approximately 5 minutes.
Personnel on site at the time had no warning of the release. They described the movement of the slide mass as fluid like and very fast.

The slide removed the powerlines on the east side of the road and the fibre optic BC Tel lines on the west side of the road. The extreme force on lines caused them to detach from the poles for 1 kilometre to the north and 500 metres to the south.



Slide debris in Slocan River
Figure 4

During the failure of the powerlines, the lines crossed the road flipping a pick-up truck on its side and knocking over a flagperson. No injuries were reported and no vehicles or persons were in the path of the failure.



Slide debris in Slocan River
Figure 5

Cause of Failure

Until the failure, the slide was attributed to weaker soils and high spring groundwater conditions. After the failure it was apparent the source of water was a consequence of natural piping of the silty sand. Three natural pipes were exposed in the scarps of the failure; one of which contained a flow of water close to that of the waterfall above the slide, the other two were dry at the time of failure.

The blockage of the "pipes" from minor ground movement forced the water to infiltrate the varved silts at the toe of the slope. With the seasonal increase in flows of the waterfall above the slide in spring, the soil became weaker (reduced effective stress), resulting in the strain movement observed.

Sufficient strain movement and/or adjacent piping had likely occurred in the spring of 2000 causing a "dam" large enough to raise the local groundwater water elevation to point where the soil strength was reduced to the point of failure. The catastrophic fluid like nature of the failure was a consequence of the saturated condition of the soils.

Post Failure

After the slide the roadway was covered three metres deep for approximately 90 metres, essentially closing the highway.

There were several slump blocks still perched after the failure causing concern for further slides. Numerous monitoring stations were placed on the slump blocks and scarps. These sites were constantly monitored and numerous sites indicated movement. The rates of movement were reviewed over time and a several zones indicated accelerating movement; pointing towards a potential failure.

Two subsequent failures did occur. Both events comprised of approximately 1500 to 2000 cubic metres of material and emanated from blocks in the rear of the scarp.

Removal of debris within the main slide was not allowed until three days after the failure due to continued movement of the area around the slide. One lane traffic was allowed at the end of the third day.

Remediation of the slide

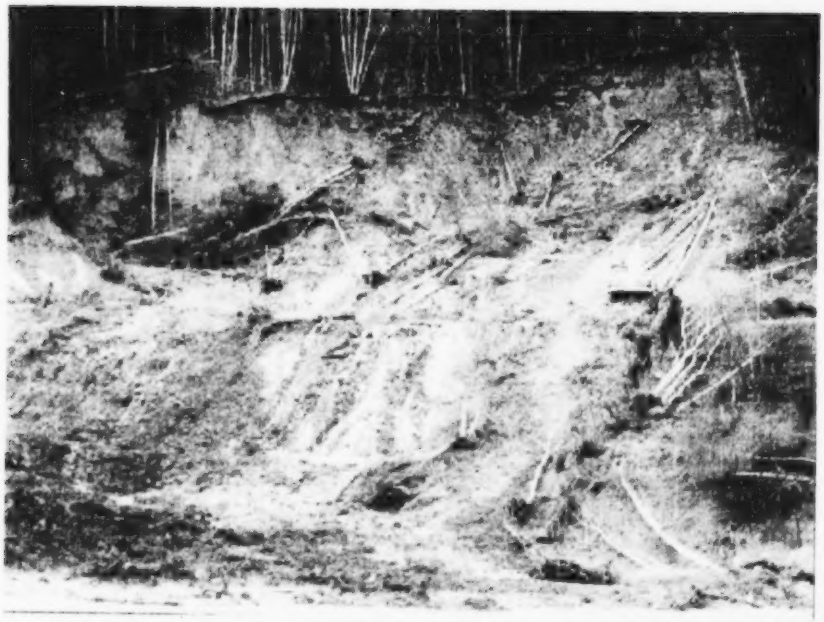
Given that the main mechanism that was thought to have caused the slide still existed (the natural piping), there was concern that failure or slumping of the back scarp above the main pipe would cause a blockage and the initiation of a similar sequence of events that lead to the original failure.

The best method for control of further failure was considered to be control of the groundwater. As outlined before, the recharge of the local groundwater was mostly controlled by the waterfall above the failure. Several scenarios for capturing and piping the flow were considered. The determination of the best option was complicated by private property issues, liability, maintenance access, costs and constructability.

Both the slide and the waterfall were within one private lot, therefore, to reduce impacts to adjacent land owners and ease the legal requirements for maintenance access, the pipe and access were constructed on a steep road directly up the slope.

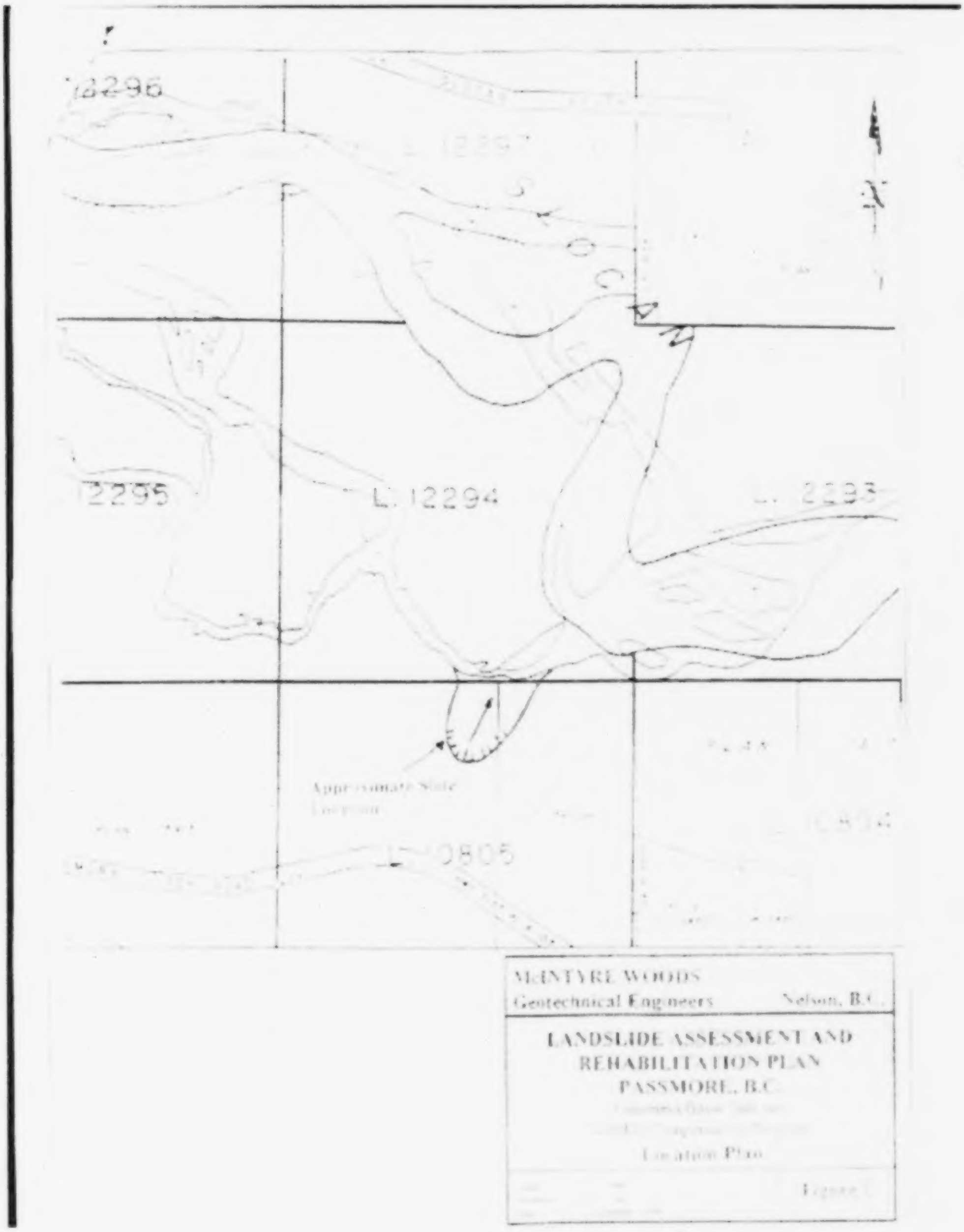
The catchment at the base of the waterfall was constructed using a basin shaped from stacked concrete sacks rebarred together and a geomembrane liner. The pipe is a smoothwall 400mm Big "O" PVC pipe comprised of 6 metre sections.

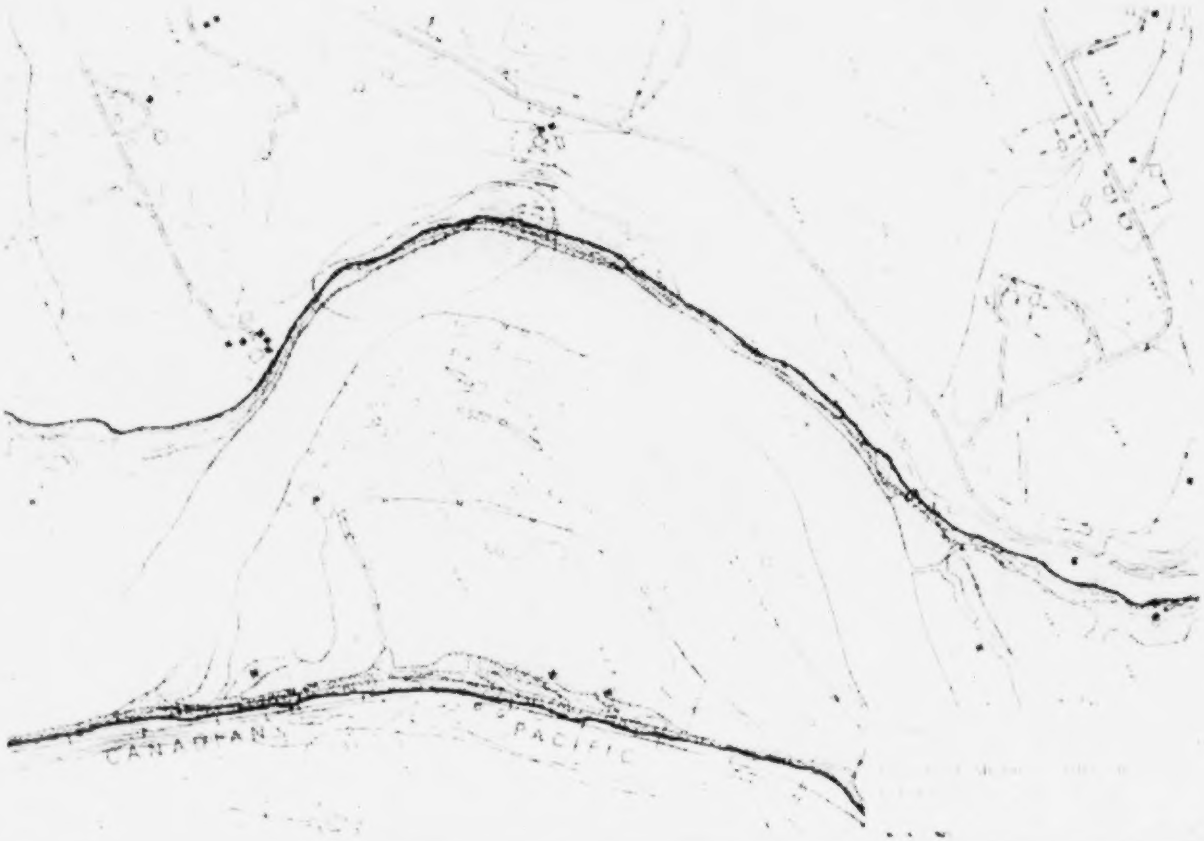
To reduce the costs and complexity of construction of the pipe over the steep rocky terrain immediately below the waterfall, the pipe was constructed above ground. To mitigate problems of tree fall and avalanche debris on the PVC pipe, the pipe was installed in a steel culvert which was anchored at the top of the slope using rockbolts and cable. The PVC pipe was secured within the culvert pipe by injecting expanding polystyrene foam at zones along the length of the pipe.

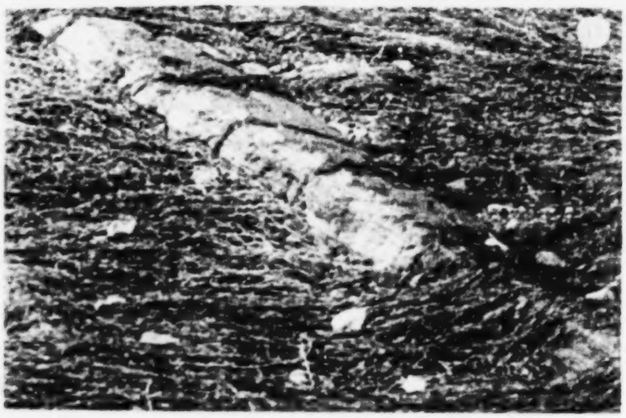


Commencement of Slide Clean-up
Figure 6

Little Slocan River Landslide, Spring 1997


12296
L. 12297
SLOCAN
12295
L. 12294
L. 2293
Approximate Slide Location
L. 0805
McINTYRE WOODS
Geotechnical Engineers
Nelson, B.C.
LANDSLIDE ASSESSMENT AND
REHABILITATION PLAN
PASSMORE, B.C.
Location Plan
Figure 1


CANADIAN PACIFIC



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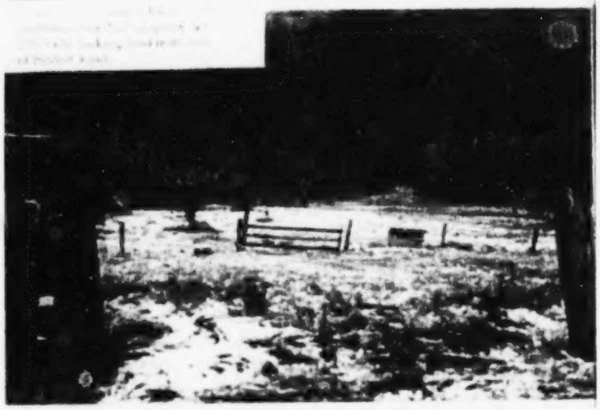


Planning level	Risk assessments
1. Overview level ("landscape" level) - Total Chance Plan - Total Resource Plan - timber supply review area - order of 100 km^2 or more time scale - rotation (≈100 y)	**Overview risk assessment for strategic planning** - identify areas with significant constraints or planning issues - identify high-risk areas where more detailed mapping or assessment needed - identify areas where no development should take place - enable estimates of rate-of-cut and timber availability - provide guidance for preparing FDPs
2. Operational plan level ("stand" level) - Forest Development Plan - access plans - deactivation plans area - usually smaller; a group of cutblocks and access roads time scale - 5 years	**Operational risk assessment** - typically based on detailed (TSIL C or better) terrain stability mapping , stream channel assessments, etc. - based on specific road alignments and cutblocks in FDP - identify need for further TSFAs, relocating roads, need for professional prescriptions, revision of cutblock boundaries or harvesting system, reserves, special deactivation needs
3. Site-specific plans and designs - one road or cutblock time scale - 1 year	**Individual risk assessments are often incorporated into TSFAs** - specific to a single design; e.g. a stream crossing; a cutblock with avalanche hazard

Perry Ridge, an Example of a Risk Assessment for Forestry Planning

D.F. VanDine[1], Peter Jordan[2], and Dwain Boyer[3]

(Published in: *Confronting Uncertainty: Managing Change in Water Resources and the Environment*, Canadian Water Resources Association, British Columbia Branch, Conference Proceedings, Oct. 27-29, 1999, Richmond, B.C., p. 255-262.)

Abstract

Perry Ridge is located in southeastern BC. Most of its uplands is Crown land, and private lands extend along its eastern base. The authors carried out a consensual overview assessment of risk to life/limb, property and water supply on the private land from proposed road building and logging on the Crown Land. Geologic hazards, as assessed by others, were grouped into 9 types and a hazard rating system was developed. Elements at risk were identified and grouped into 3 categories (life/limb; property; and water supply), and a consequence rating system was developed. For each of the 32 hydrological units identified, existing risks were assessed by combining the hazard rating for each of the 9 types of hazardous events with the consequence rating for each of the 3 groupings of elements at risk. The anticipated risks following proposed logging activities were then assessed, and alternatives suggested. This is the first time in BC that such a risk assessment has been carried out as part of forest development planning

INTRODUCTION

Perry Ridge is located in the Slocan Valley in the West Kootenay region of British Columbia . The relatively flat-topped ridge is approximately 25 km long, 9 km wide and ranges in elevation from 500 m to 2100 m. Most of its uplands is Crown Land and is included in the B.C. Ministry of Forests (MOF), Arrow Forest District, Small Business development area. (Under the "Small Business" program, provincial forest land is managed directly by the MOF, which conducts all planning, road-building, and silviculture activities, and makes individual timber sales available by bid.)

Privately owned land extends along the base of, and in places part way up, the east side of Perry Ridge. Much of the private land has been cleared for pasture or cultivation, or has been logged, and numerous residences, with associated water supply intakes, are located along the base of the ridge.

Forest development in the Slocan Valley is an unusually contentious issue. Some well-publicized anti-logging protests have occurred at Perry Ridge and elsewhere in the Slocan Valley. Residents' concerns include possible impacts on water quality, and risks from landslides from logged areas and roads.

The Arrow Forest District is undertaking a comprehensive planning process for forest development on Perry Ridge, which significantly exceeds the requirements of the Forest Practices Code. This has included several mapping projects which addressed geologic and hydrologic hazards both on the ridge and within the adjacent populated valley bottom. To facilitate public participation, an advisory committee, the Perry Ridge Local Resource Use Planning Table ("the Table") was set up, including representatives from various interest groups in the community. The risk assessment described in this paper was conducted for the Table as part of this planning process. The Arrow Forest District made an effort to keep the Table involved at every step of the study, and to make the results of the risk assessment and the underlying hazard studies accessible to the public.

---

[1] VanDine Geological Engineering Limited, 267 Wildwood Avenue, Victoria, B.C., V8S 3W2

[2] B.C. Ministry of Forests, 518 Lake St., Nelson, B.C., V1L 4C6

[3] B.C. Ministry of Environment, Lands and Parks, 333 Victoria St., Nelson, B.C. V1L 4K3

The authors of this paper were asked to form the Perry Ridge Technical Review Panel ("the Panel"). The purpose of the Panel was to use the results of the geologic hazard studies, and other information, to carry out an overview geologic and hydrologic assessment of existing risk to life/limb, property and water supply and anticipated risks from road building and logging on Crown Land as proposed in a Total Chance Plan (TCP). Based on the results of the risk assessment, and to the level of information available, the Panel was asked to suggest alternatives to the TCP and to make any other relevant recommendations.

For practical purposes, forest planning for a new development area has three stages:

1. An overview or Total Chance Plan (TCP) stage. A TCP is a hypothetical forest engineering plan to efficiently develop the timber in a planning area, over the entire period of rotation of the forest. It is based on existing inventory information, such as forest cover and topographic maps, and air photo interpretation. It may be prepared several years or decades before development.

2. A Forest Development Plan (FDP) is an operational plan which identifies specific roads and cutblocks, to be constructed and harvested over the next several years, for a single development area. It is based primarily on field work. The content and information requirements of a FDP are specified in detail by the Forest Practices Code.

3. Road designs and logging plans, for individual road permits and cutting permits issued by the MOF.

Most mapping and watershed-scale assessment of geologic and hydrologic hazards and related environmental concerns is done at the FDP stage, including terrain stability mapping and watershed assessments as required by the Forest Practices Code. Although risk assessments are not required by the Code, in theory they could be part of any of the three planning stages. In practice, simple risk assessments are commonly carried out during the third stage, as part of engineering work on individual high-hazard road segments or stream crossings.

The Perry Ridge Risk Assessment was done during the initial stage of planning. Its main objectives were to identify, at the scale of watersheds or other suitable geographic units (from about 1 to 13 km^2), existing geologic and hydrologic risks or risks that would result from proposed forest development; to identify constraints to development which would be imposed by these risks; and to suggest alternatives and recommendations to the TCP to reduce these risks.

This is the first time in British Columbia that such an overview risk assessment has been carried out as part of the forest development planning process. As such, the purpose of this paper is not to present the results of the risk assessment (those are presented elsewhere, refer to Boyer, Jordan and VanDine, 1999), but to describe in some detail the method the Panel used to carry out its assignment.

Over the past two decades, a number of risk assessment studies have been conducted in British Columbia, primarily for highways and other transportation planning, hydroelectric development, and municipal planning. The theoretical basis of these studies, and some examples, are reviewed by Morgan (1991), Morgan et al (1992), and Cave (1992). Although past studies have been done for industries or activities other than forestry, the basic principles are applicable to forestry planning. In the literature on risk assessment, there is some variability in the details of the methodology used, particularly in the definitions used for "High", "Moderate", and "Low" hazards and consequences. In this study, the Panel attempted to apply definitions consistent with past studies, with due consideration to the variety of hazards examined, and the differences in scale of planning unit to which the past studies were applied.

Risk is the product of hazard and consequence, where hazard is the probability or likelihood of a hazardous event occurring, and consequence is the effect of that event. Consequence is a combination of the elements at risk and the severity and/or frequency of the hazardous event on those elements at risk. For hazardous events that occur frequently in the same location, such as floods and snow avalanches, and where historical data exists, quantitative risk assessments may be appropriate. For Perry Ridge, however, the hazardous events are relatively infrequent and/or the historical data is lacking. To accommodate this difficulty the Panel carried out a consensual qualitative risk assessment based on available information and empirical evidence combined with the experience and judgement of the Panel. The consensual aspect of this risk assessment was intended to minimize any biases, and to provide an "average" of three people's qualitative judgments.

BACKGROUND DATA AND METHODOLOGY

The study area covered approximately 70 km^2 composed of approximately 44 km^2 of Crown Land and 26 km^2 of private land along the east side of Perry Ridge.

In general, on most of the ridge, the level of geomorphic activity is low. Landslides and other sediment sources are scarce. However, many creeks are deeply incised in bedrock, and their channels and fans have debris flow deposits. In the valley bottom, there are extensive deep glacial deposits, which are subject to a variety of potentially hazardous processes, including slumps, debris slides, and sinkholes.

No forest development has taken place on Crown land on the upper part or east side of Perry Ridge, although construction of a road into the area from the north has begun. Most of the ridge was burned by large fires 80 to 100 years ago, and timber in the burned areas is now nearing maturity.

Hydrologic Units, Zones of Influence, and Forest Development Areas

To relate the risks to the geography, the Panel divided the study area into 16 watershed units and 16 "face" units, a total of 32 hydrologic units. The latter are located between the watersheds, and most do not contain obvious surface watercourses. The lowermost point of the watershed units was generally located at the furthest upstream water intake. The lower boundary of the face units was assumed to be the topographic break between the Perry Ridge slope and the valley bottom, which is also typically the boundary between forest and agricultural land. For each hydrologic unit the watershed/face area was calculated and the H60 elevation determined. This is the elevation above which 60% of the watershed lies. It is used to give greater weight to forestry operations at higher elevations which receive greater snowfall.

The approximate areas downslope of the hydrologic units that could potentially be affected by surface water, groundwater, and runout resulting from various events originating upslope were delineated by the Panel and referred to as zones of influence. The zones of influence were delineated manually using 1:10,000 scale, 10 m contour maps, 1:5000 scale, 2 m contour valley bottom floodplain maps and 1998 air photos. In the absence of other information, groundwater flow was approximated from surface contours. The zones of influence between adjacent watershed and face units commonly overlap.

The Total Chance Plan (D.S. Spencer Forestry Consulting Ltd, 1998) extended the traditional TCP such that development of the timber also considered methods to partially reduce effects on some non-timber resources. The Perry Ridge TCP identified over 300 hypothetical cutblocks and over 100 km of logging roads. To simplify this TCP, the Panel divided the plan into 18 forest development areas based primarily on access, so that conceivably each area could be developed independently.

Equivalent Clearcut Area (ECA) is a concept widely used in forest hydrology to estimate the per cent of a watershed that has been clearcut or is equivalent to the clearcut condition. ECA calculations consider silvicultural system (clearcut or partial cut), harvesting system, and amount and density of regeneration (Interior Watershed Assessment Procedure Guidebook, MOF and MELP, 1995). For each hydrologic unit, the Panel estimated an ECA Index, which is an indicator of the extent of existing and proposed logging and its hydrologic effect. The following assumptions were made: the areas above H60 were weighted 50% higher than the areas below H60; between 40% and 80% of the private land had been logged, based on estimates made from air photos; on Crown Land it was assumed that 30% of the volume of timber in the development area would be logged during the initial development; logging would not be concentrated in any one hydrologic unit; logging a given volume of timber would have the same effect whether it is clearcut or selectively logged; and reserves identified in the TCP would not be logged.

Geological Hazards

Key documents used for the hazard assessment included: Detailed Terrain Stability Map at 1:20,000 scale (Wehr, 1985; updated by S. Chatwin Geoscience Ltd, 1998b); Stream Channel Assessments at a scale of 1:10,000, for 14 of the 16 streams (S. Chatwin Geoscience, 1998a); Geological Hazards Mapping on the private land at a scale of 1:25,000 scale (Apex Geoscience, 1998); Floodplain Mapping along the Slocan River at 1:5000; and 1:15,000 scale 1998 air photos. Using this information the geological hazardous events were grouped into 9 different types, in 3 categories:

- **Primarily water related events:** peak flow/flood; sediment yield
- **Primarily slope/channel related events:** debris slide into a stream; debris flow down a stream; debris flood/avulsion along stream channel; open slope landslide (any type of landslide that occurs on an open slope above the valley bottom and does not enter a stream); snow avalanche
- **Primarily valley bottom related events:** valley bottom landslide; sinkhole development

In each of the above categories, the likelihood or probability of a particular event occurring was rated somewhat differently, although all were rated strictly on the occurrence of an event and independent of the magnitude of the event. One of the challenges of the Panel was to establish a common hazard rating system for all 9 event types that could be applied to an entire hydrologic unit. Hazards were relatively rated as "High", "Moderate", "Low", "Very Low" and "None".

The anticipated hazard with logging on Crown Land as proposed by the TCP was then assessed, based on the existing hazard plus an inferred linkage to forest development. This linkage was subjectively determined from the TCP, including the proposed road system, harvesting system, the estimated ECA Index as a result of logging, and the location of roads or logging with respect to mapped hazard polygons. The linkage was relatively rated as "Low", "Moderate" and "High". Assumptions included the 30% removal of timber in development areas, as discussed above, road building and logging in accordance with the Forest Practices Code, and the fact that adjacent zones of influence often overlap. The effects of present and/or future land use activities on the private land were not considered.

An example summary of existing hazards, inferred linkage to forest development, and the anticipated hazards after logging as proposed by the TCP is shown in Table 1. To illustrate the concept of linkage, using this example: the linkage of "valley bottom landslide" to forest development is low because the proposed development does not occur where it could affect the polygons mapped high for this hazard; and the linkage of "sediment yield" is high because there are seven proposed road crossings of the creek. Low, moderate, and high linkages increase the hazard class by zero, one, or two classes respectively. (The series of +'s are graphic symbols equivalent to arrows of various lengths.)

Table 1: Hazards summary for Watson Creek

No.	Event type	Existing hazard	Linkage to forest development	Hazard with TCP
	Primarily water related events			
1	Peak flow/flood	Moderate	+++	High
2	Sediment yield	Very Low	++++++++	Moderate
	Primarily slope/channel related events			
3	Debris slide into stream	Moderate	+++	High
4	Debris flow down stream	Moderate	+++	High
5	Debris flood/avulsion along stream	Low	+++	Moderate
6	Open slope landslide	Low	+	Low
7	Snow avalanche	None		None
	Primarily valley bottom related events			
8	Valley bottom landslide	High	+	High
9	Sinkhole	None		None

Notes: Linkage to forest development: + (Low); +++ (Moderate); ++++++++ (High)

Elements at Risk and Consequences

The elements at risk that the Panel were asked to consider were: life and limb, property and water supply. They were mapped as follows: residences and other buildings were located from a high-resolution satellite photo, 1998 air photos, and 1:5000 floodplain maps; roads, utilities, and agricultural land were obtained from forest cover maps; and water license locations were obtained from the Ministry of Environment, Lands and Parks water rights maps (excluding water wells, as they are usually not recorded).

This mapping was accompanied by several stated assumptions and limitations. The intent was to have a uniform level of information across the study area (and within each zone of influence), rather than to accurately map each element at risk. Only existing elements at risk were considered; possible future elements such as new subdivisions were not.

Consequences were rated by the Panel as "High", "Moderate", and "Low" based upon the elements at risk and the inferred severity/frequency of the type of events to which those elements at risk are, or may be, exposed. If the consequences were assessed to be "Very Low", they were not noted. The relative ratings were not intended to be compared among the three groupings of elements at risk. Some examples of consequences are as follows (this is a partial list only):

- Consequence to life and limb: High - death; Moderate - serious injury; Low - minor injury.
- Consequence to property: High - destruction of multiple residences; Moderate - destruction of single residence, or damage to multiple residences; Low - damage to single residence.
- Consequence to water supply: High - destruction of multiple water intakes, or very high increase in turbidity; Moderate - destruction of a single water intake, or high increase in turbidity; Low - damage to a single water intakes, or moderate or low increase in turbidity.

RISK ASSESSMENT

The risk assessments for each of the 32 hydrologic units were carried out with the help of three 3 X 4 risk matrices: one relating to life and limb, one relating to property and one relating to water supply. Example risk matrices for one hydrologic unit are shown in Table 2.

Table 2: Risk matrices for Watson Creek

Hazard	Consequence to Life and Limb			Consequence to Property			Consequence to Water Supply		
	High	Mod	Low	High	Mod	Low	High	Mod	Low
High	VH	H +	M	VH	H	M + +	VH	H + + +	M
Mod	H	+ + 4 M		H	M	+ + + + 1 4 +	H	+ + + + + + 1 3 4 + +	
Low	M			M		+ + 5	M	+ + + + + 5 + +	+ 6
Very Low								+ + 2	

The numbers in Table 2, correspond to the 9 types of hazardous events (see Table 1). The location of the numbers indicate the existing risk rating (that is, with no logging on Crown Land). Event numbers appearing in Table 2 but not in Table 1 indicate consequences that were assessed to be "Very Low".

The risks with logging activities on Crown Land as proposed by the TCP were then assessed and entered in the matrices. It was assumed that the consequences would not change after logging, only the hazards, and the amount the hazards would change was related to the linkage to forest development. The changes to the existing hazard, and therefore risk, are shown graphically in the risk matrices by a series of ascending "+'s", as explained for Table 1. Note that as for consequences, relative risks were not to be compared among the three groupings of elements at risk.

It is important to note that the risk ratings are applied conservatively across an entire hydrologic zone of influence, and do not necessarily apply to an individual element of risk within that zone. The risk ratings are relative terms only, and cannot be translated into a numerical probability of a consequence occurring at any particular location. Several things would have to occur, and several conditions would have to be met, before these risks are actually realized.

Take, for example, a house located in a zone of influence near the base of the east side of Perry Ridge. Assume the hazard of an open slope landslide in the hydrologic unit above the zone of influence is rated as "High" (although the "High" open slope landslide hazard has been applied to the entire unit, it probably only refers to a portion of that hydrologic unit, and the remainder has a lower hazard rating). For a "Moderate" property consequence to occur, and hence the house to be at "High" risk: the open slope landslide *has to* occur; it *has to* occur at a location above the house; it *has to* travel far enough down the slope to reach the house; it's flow path *has to* be in line with the house; *and it has to* have enough energy when it reaches the house to destroy it. For a "High" consequence to life and limb to occur, and hence life and limb to be at "Very High" risk, *in addition to the above occurrences and conditions*: someone *has to* be in the house at the time it is destroyed; *and* the open slope landslide *has to* have enough energy to not only destroy the house but to kill the person in the house.

Where "High", "Very High", and "Moderate" risks were identified, and based on the information contained in the background documents and the experience of the Panel, alternatives to the logging or road building on Crown Land as proposed in the TCP were suggested and recommendations made to reduce the effects of the proposed forest development on life/limb, property and water supply. The effect of the alternatives on the feasibility (economic or otherwise) of the development plan was not considered.

The difference between alternatives and recommendations, is that the alternatives were suggestions to be considered by the Table at subsequent planning meetings, while the recommendations should be carried out, in many cases prior to logging regardless of the details of the final forest development plan.

Examples of suggested alternatives are: eliminate logging in specific areas; limit the ECA in specific areas (equivalent to reducing the rate of cut); add riparian reserve zones; modify road locations; eliminate specific stream crossings; eliminate specific roads and instead consider skyline logging, helicopter logging, or no logging.

Examples of recommendations are: extend geological hazard mapping in specific areas; carry out stream channel assessments on specific streams not already assessed; determine stream courses or watershed boundaries in some locations where they are poorly mapped; do Terrain Stability Field Assessments to address specific hazards; pay special attention to the location, design and construction of specific logging roads and creek crossings; design and construct specific logging roads to higher drainage control standards than normal; minimize ground disturbance associated with skidding in specific areas. Most recommendations were aimed at doing further geotechnical studies, or detailed planning or design in excess of minimum Forest Practices Code standards, to reduce identified hazards such as sediment production or landslides.

This risk assessment did not address the acceptability of risk. Thresholds of risk acceptability should be established by government, which must incorporate appropriate socio-economic and environmental factors into its decision making.

CONCLUSIONS AND DISCUSSION

Obvious questions to ask at the conclusion of such a study are: Was the process useful? Is it applicable to other forest planning areas? And considering that this was the first such study done for forestry purposes, should any major changes in the methodology be made for future studies?

Having a risk assessment study such as this done at the initial, or TCP, stage of planning helps identify major constraints, and set priorities for further mapping and information gathering for specific Forest Development Plans.

In considering possible future studies elsewhere, one should keep in mind that the information used in the Perry Ridge Risk Assessment exceeded what is normally available at this stage of planning, especially the stream channel assessments and hazard mapping on private land. The methodology we used, therefore, may be more applicable to studies for smaller, high risk areas (such as populated alluvial fans) done at the FDP stage. At this stage, field work should be an important component of the study, and would be targeted at specific roads and harvesting areas. Future studies at the overview level are likely to be simpler, commensurate with the information available.

We found the consensual approach, using a 3-member panel, to be useful in dealing with the inevitable lack of quantitative hazard data. However, the process is time-consuming and expensive. We found the level of information available for the study, and its consistency and quality, to be suitable for the purpose of this study. However, future risk assessments in other areas are likely to have less rather than more information available. Considering the large areas of land with which forestry planning deals, it is unlikely that the routine collection of more detailed geologic and hydrologic information would be affordable for most planning studies.

We found that dealing with the public involvement aspects of this study introduced an unexpected amount of additional time (and therefore cost to the proponent, the Arrow Forest District). We found that the public, and even some forestry and engineering professionals with an interest in the process, had difficulty understanding the concepts of probability on which risk assessment is based, and the limitations of such a study. We also found that some sectors of the public had a very low tolerance for any risks associated with proposed development, and that they did not understand the concept that damage to a single property, which to them personally is of very high consequence if it is their own property, might be considered only a "Moderate" consequence in the context of a larger planning unit. This is not unexpected, and it is probably inevitable in any such study that attempts to keep citizens informed about risks that affect them locally.

A change that might reduce some of these problems is to develop consistent and accepted definitions of what types, magnitudes, and frequencies of hazard constitute "High", "Moderate", and "Low", and similarly, definitions for consequences. This change can only come about from the accumulated professional experience of doing a number of such studies.

REFERENCES

Apex Geoscience Consultants Ltd, 1998. Geological hazards mapping of the Slocan Valley, Phase I. Report and maps prepared for MOF Arrow Forest District, Castlegar, B.C.

Boyer, D., Jordan P. and VanDine, D.F., 1999. Perry Ridge risk assessment. Report and map prepared for the Perry Ridge Local Resource Use Plan Table, available from MOF Arrow Forest District, Castlegar, B.C.

Cave, P.W., 1992. Natural hazards, risk assessment and land use planning in British Columbia: progress and problems. *In* Geotechnique and Natural Hazards, a Symposium sponsored by the Vancouver Geotechnical Society and the Canadian Geotechnical Society, May 6-9, 1992. Bitech Publishers, Vancouver, p. 1-11.

S. Chatwin Geoscience Ltd. 1998a. Perry Ridge stream channel survey. Report and maps prepared for MOF Arrow Forest District, Castlegar, B.C.

S. Chatwin Geoscience Ltd. 1998b. Upgrade of TSIL C mapping and surface soil erosion hazard mapping for the east side of Perry Ridge. Maps prepared for MOF Arrow Forest District, Castlegar, B.C.

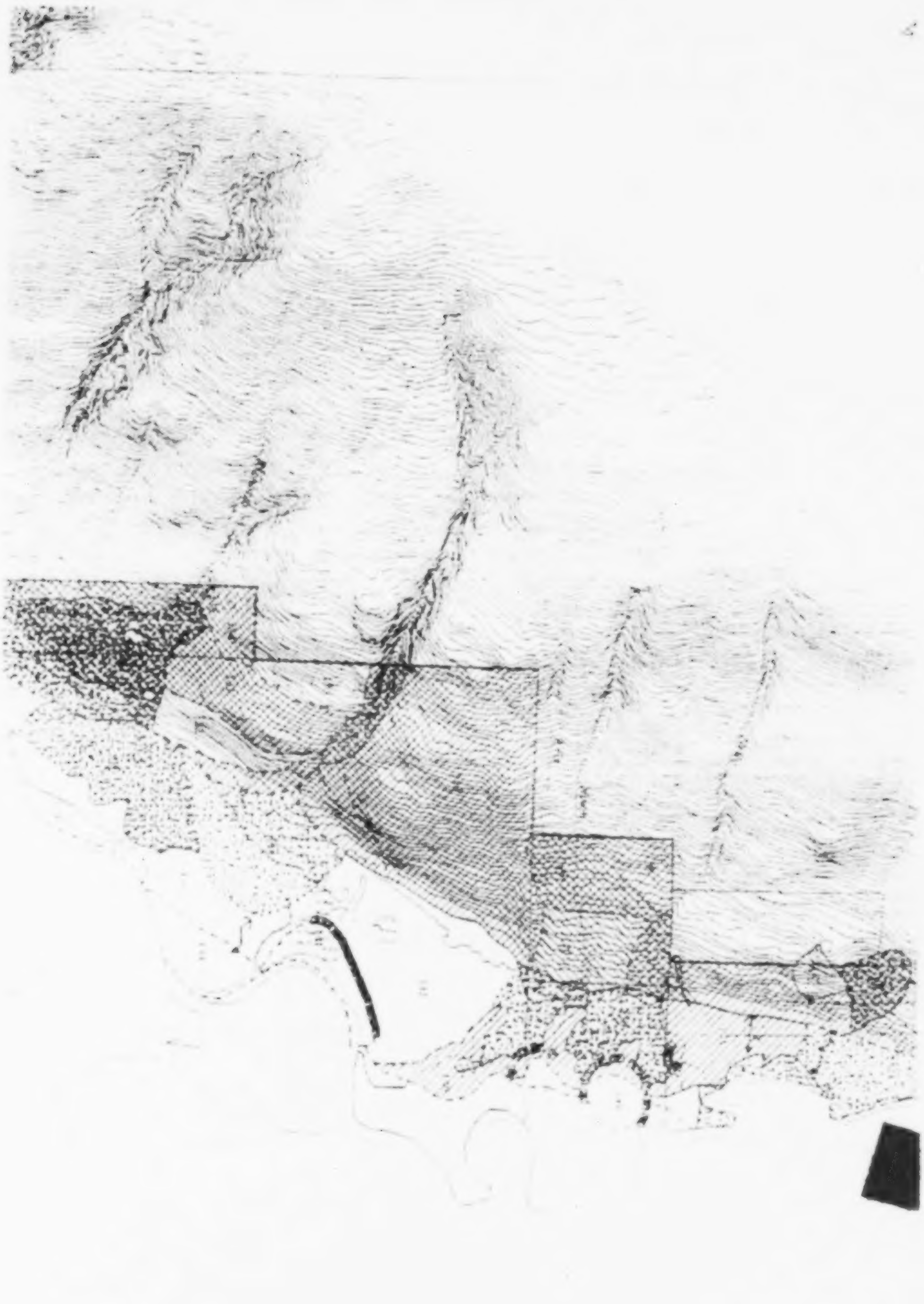
Forest Practices Code of British Columbia, 1995. Interior watershed assessment procedure guidebook (IWAP). British Columbia MOF and MELP.

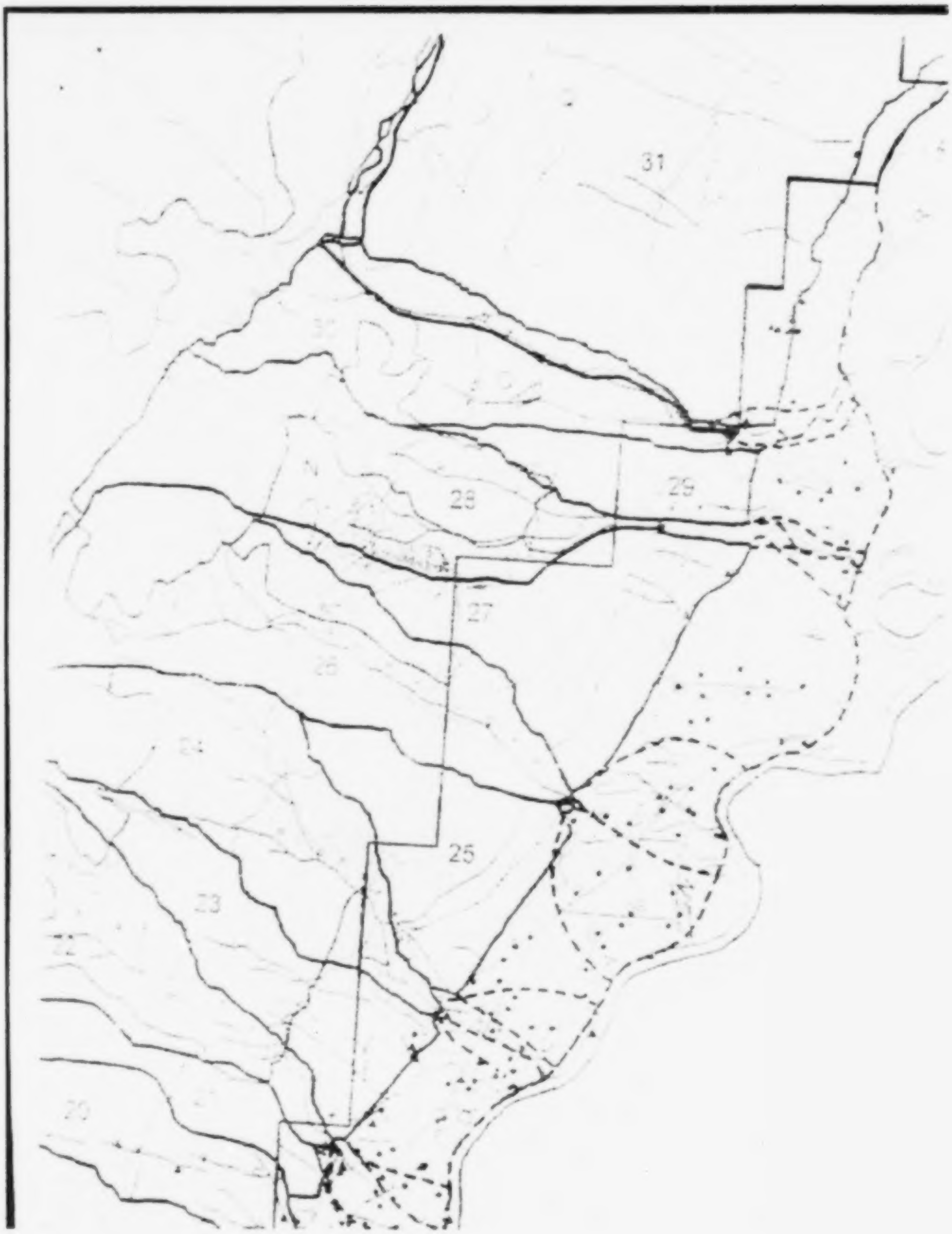
Morgan, G.C., 1991. Quantification of risks from slope hazards. In Geologic Hazards in British Columbia, Proceedings of the Geologic Hazards '91 Workshop, Feb. 20-21, 1992, Victoria, B.C. British Columbia Geological Survey Branch, Open File 1992-15, p. 57-67.

Morgan, G.C., Rawlings, G.E., and Sobkowicz, J.C., 1992. Evaluating total risk to communities from large debris flows. *In* Geotechnique and Natural Hazards, *op cit.*, p. 225-235.

D.S. Spencer Forestry Consulting Ltd, 1998. Engineering plan report, Perry Ridge total chance plan. Report and maps prepared for MOF Arrow Forest District, Castlegar, B.C.

Wehr, R., 1985. Terrain survey: Perry Ridge, preliminary assessment. Report and maps prepared for Slocan Forest Products, available form MOF Arrow Forest District, Castlegar, B.C.

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Memphis Creek
Cape Horn Bluffs
Debris Flows

May 30, 1990

Memphis Creek - Cape Horn Bluffs

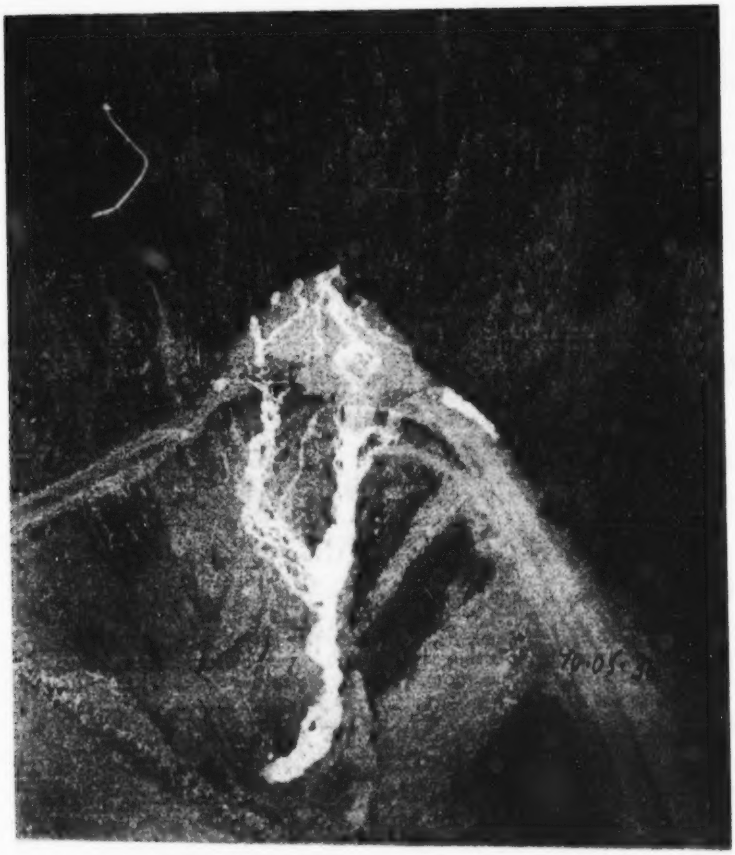


Photo 10 Torrent debris retained by old highway. Old highway washed out by torrent. Debris accumulated between old and new highway.

Memphis Creek - Cape Horn

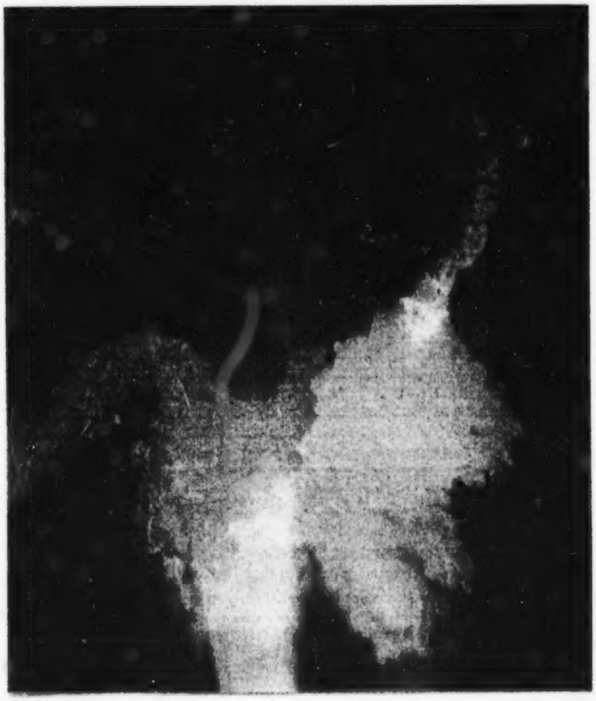
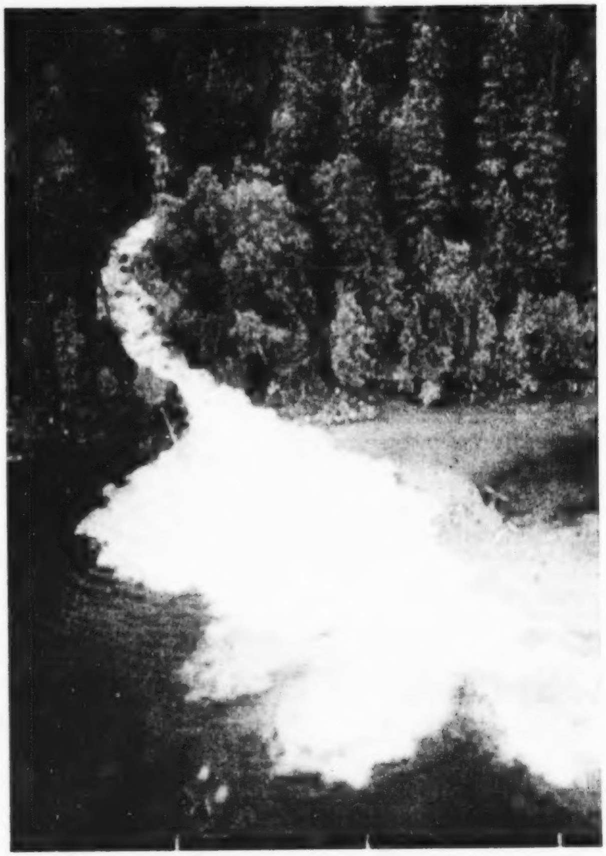


Photo 11 Torrent debris entering Slocan Lake after passing through highway culvert.



Memphis Creek Upslope

Photo 2 Cutblock in photo 1 on right, lower edge of photo. Switchback road (switchback in photo 3) accumulating runoff which ends up in stream crossing cutblock in photo 1.

GEOLOGICAL ENGINEERING ASSESSMENT OF THE
OTTAWA HILL (SLOCAN VALLEY)
DEBRIS TORRENTS OF MAY 1990

A Report to
BC Ministry of Forests
Arrow Forest District

...OGICAL ENGINEERING SERVICES

June 1990
VGE File 90103

Landslide Study - Cape Horn Bluffs Area

Detailed Report for

Ministries of Forests and Environment

by

Mike Curran, P.Ag. Research Pedologist
Brian Chow, P.Eng. Field Engineer
Dave Toews, R.P.F. Research Hydrologist

B.C. Min. Forests

and

Dwain Boyer, P.Eng, Engineering Section Head
Water Management Branch,

B.C. Min. Environment

July 20, 1990

Nelson, B.C.

APRIL 1, 1991

LEE E. BENDA
600 N.E. 78th ST.
SEATTLE, WASHINGTON

EBA Engineering Consultants Ltd.

SIERRA LEGAL DEFENCE FUND
Debris Flow Damage,
Simkins Property,
Lot 14 Slocan Valley

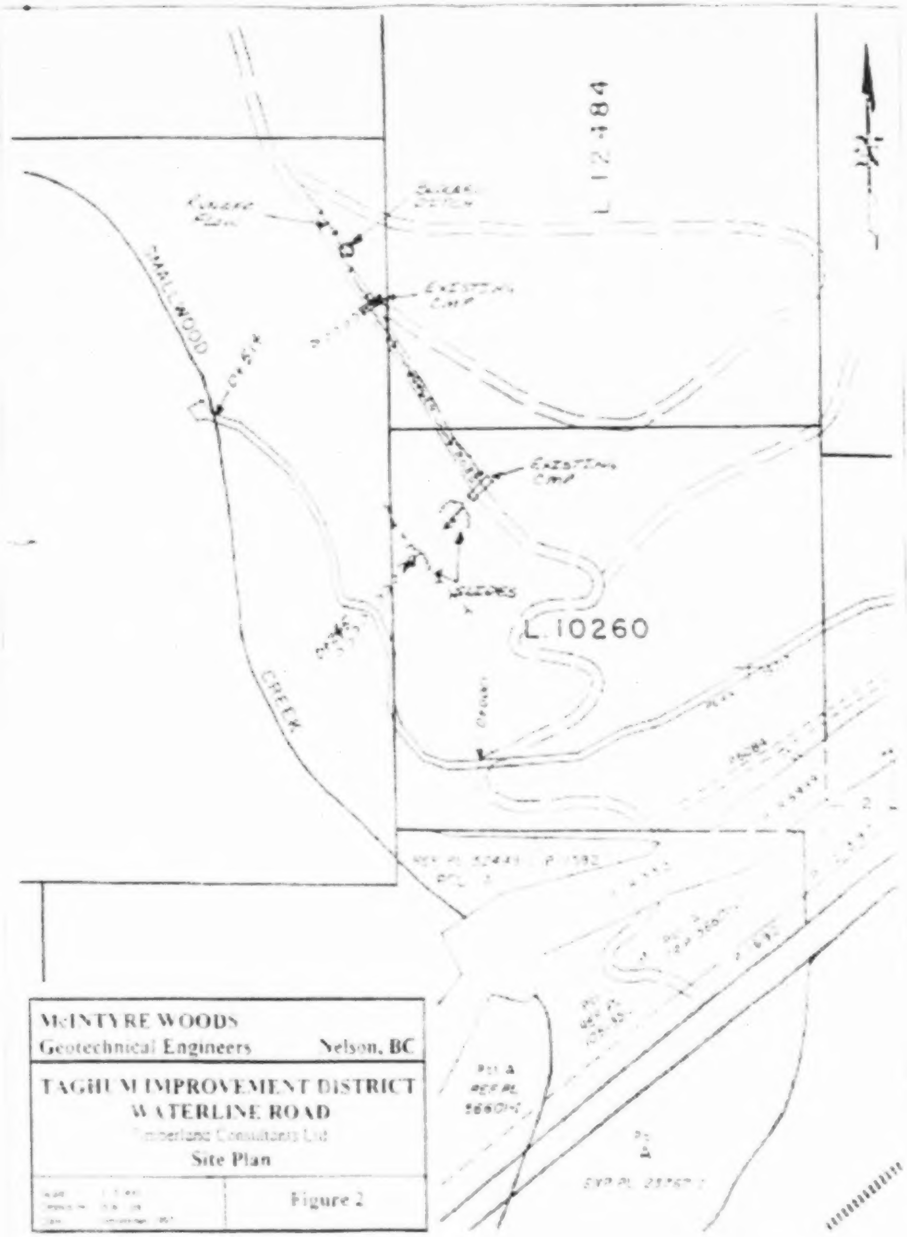
July 1994

File: 0806-86491A

Suite 550, 1100 Melville Street, Vancouver, B.C. V6E 4A6
• Telephone (604) 685-0275 • FAX (604) 684-6241 •

SIERRA LEGAL DEFENCE FUND
Debris Flow Damage,
Manyskies Property,
Lot 11722, Slocan Valley

Smallwood Creek Landslide – March 26, 1997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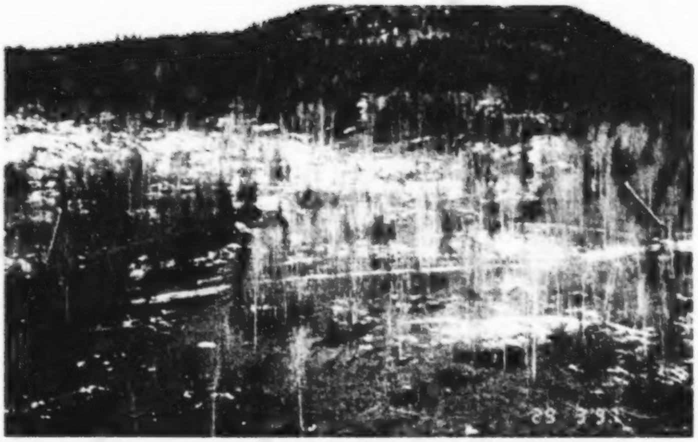
WATERLINE ROAD
Timberland Consultants Ltd
Site Plan
Figure 2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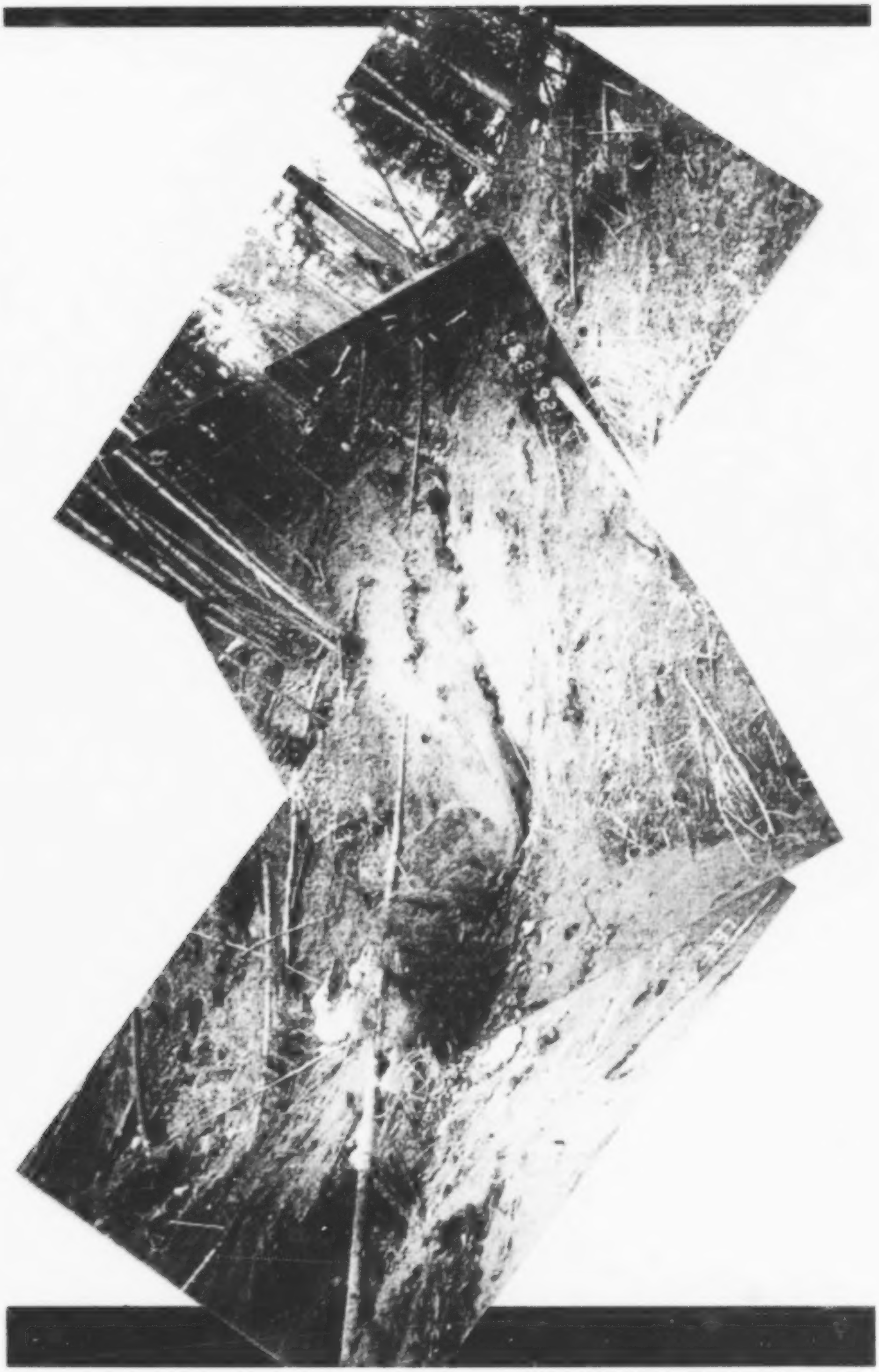
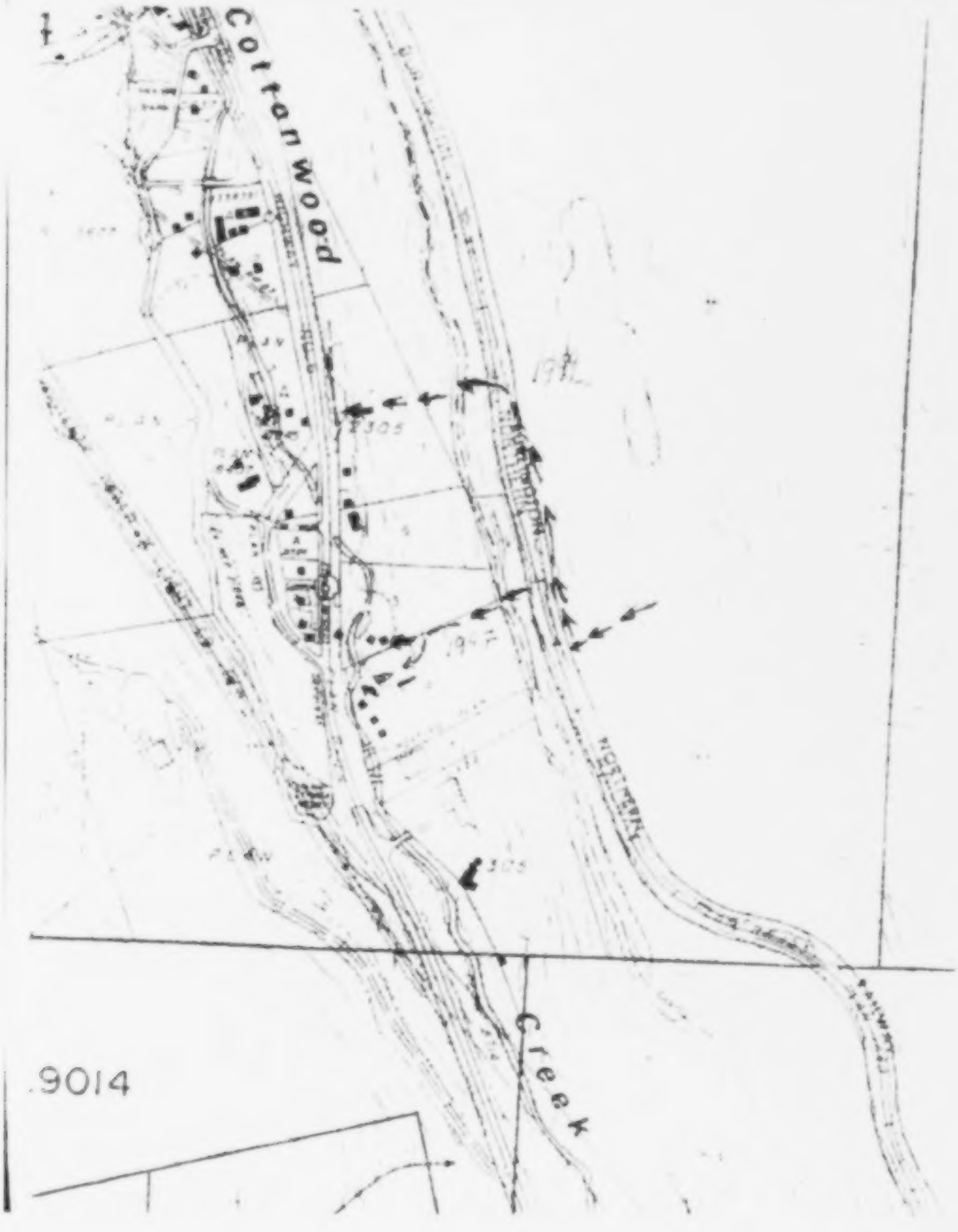


Cottonwood Creek Landslide - April 1997 & April 1999



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